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Healthy Homes Issues: Residential Assessment

HEALTHY HOMES INITIATIVE (HHI) BACKGROUND INFORMATION

Version 2

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Preface

In 1998, Congress appropriated funds and directed the U.S. Department of Housing and Urban Development (HUD) to “develop and implement a program of research and demonstration projects that would address multiple housing-related problems affecting the health of children.” In response, HUD solicited the advice of experts in several disciplines and developed a preliminary plan for the Healthy Homes Initiative (HHI). The primary goal of the HHI is to protect children from housing conditions that are responsible for multiple diseases and injuries. As part of this initiative, HUD has prepared a series of papers to provide background information to their current HHI grantees, as well as other programs considering adopting a healthy homes approach. This background paper focuses on residential hazard assessment, and provides a brief overview of the current status of knowledge on:

- Integrated assessment of residential hazards
- Current methods and models for assessing residential hazards
- Research needs in the field of residential hazard assessment.

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Healthy Homes Issues: Residential Assessment

1.0 INTRODUCTION

Scientific research has established that residential hazards have a significant impact on public health. Other background papers prepared for HUD's Healthy Homes Initiative summarize information regarding the extent of residential hazards and methods to reduce these hazards for asthma, injuries, mold, pesticides, and carbon monoxide. This background paper focuses on current methods for assessing residential hazards, including a brief introduction to issues associated with an overall home hazard assessment, as well as assessment of a particular hazard, such as carbon monoxide, or a particular health endpoint, such as asthma. Familiarity with current methods to assess residential risks from lead exposure is assumed. The purpose of this paper is to provide a brief introduction to the issues associated with extending a residential risk assessment for lead to include other residential hazards, with an initial focus on injuries, allergens, mold, pesticides, and carbon monoxide.

The sections that follow provide an overview of some currently available tools for assessing hazards in the home, including discussion of several assessment methods that are more typically employed in environmental research settings. The level of rigor involved in assessing hazards in a research setting generally surpasses that which is needed for programmatic or public health use. From a housing or public health perspective, the level of rigor involved in a home assessment will be constrained by the need for cost-effective methods that are sufficient to allow for the identification of a hazard in the home environment. At this time, low-cost methods for routine assessment of some residential hazards (e.g., mycotoxins) have not yet been fully developed or are not readily available for use by public health professionals. This overview provides the reader with an overall picture of the range of assessment technologies that are available, from both a research and programmatic perspective.

2.0 COMPREHENSIVE ASSESSMENT OF RESIDENTIAL HAZARDS

An integrated, overall assessment of the degree of hazard associated with a home would optimally involve judgment of 1) the relative risk of different hazards (including consideration of sensitive populations), 2) the nature and extent of the individual hazards (e.g., concentrations of contaminants), and 3) interactions or synergisms between the individual hazards.

In general, specific methods for ranking and characterizing the overall hazard in a home have not been well defined. Some factors that have been considered include:

- Evaluating the overall degree of the hazard associated with a home.
 - Epidemiological and clinical data (illness, injury, biological markers).
 - Environmental measurements of toxicants, allergens, and molds.

- Measured changes in the condition of a home (indoor-outdoor temperature and humidity, ventilation flow rates, energy efficiency).
- Resident comfort and behavior (physical comfort, changes in behavior).

- Specifying risk management options.
 - Cost of treatment to mitigate hazards.
 - Avoided costs (repairs to moisture damaged buildings, avoided medical treatments).
 - Other economic data (healthcare costs, housing value).

2.1 Issues Associated with Comprehensive Home Assessment: Multiple Exposures, Relative Risk, and Overall Health Hazard

A major challenge for specifying an overall healthy homes assessment is that occupants of houses receive exposures to multiple agents that may interact physically or chemically with each other or their environment, or that may act synergistically (NAS, 2000). In contrast, assessment of these hazards in a home typically focuses on a single agent at a time, and thus may underestimate the overall health hazard an individual may face in a given environment. For example, asthmatic individuals may react to 20 to 50% of the particles they inhale from indoor air; however, a single allergen such as dust mite allergen likely accounts for less than 10% of the particles in their environment. Therefore, measurement of a single allergen may underestimate the total allergen load by two- to five-fold (O'Meara and Tovey, 2000).

Issues associated with characterizing the relative importance of individual home hazards in an overall home hazard assessment are not extensively discussed in the scientific literature. In a study that focused on model approaches for ranking relative risk in the home, researchers at the Harvard Center for Risk Analysis attempted to comparatively rank ten home hazards covered in the popular media, on the basis of the weight of scientific evidence from the literature, the number of Americans who might die each year (assuming the hazard is real), and the annual chance of premature fatality for highly susceptible populations (1996). Nonfatal effects were not considered in this model. The investigation resulted in the following ranking from highest to lowest perceived risk: radon gas, falling, poisoning, fires and burns, suffocation, firearms, environmental tobacco smoke, formaldehyde gas, insulation fibers, and electric and magnetic fields from power lines. The researchers noted that public perceptions of home risks often differ significantly from what the evidence suggests as the true home risks; this has implications for both the need and content of education interventions in homes. However, a severe limitation of this study, as acknowledged by the researchers, was the lack of inclusion of non-fatal effects, which would provide a much more complete understanding of overall risks.

Jones (1998) assessed the potential usefulness of the “Hazard Analysis-Critical Control Point (HACCP)” risk analysis technique, which had previously proven effective in the food industry, to define hazards and rank microbiological risks in the home. In assessing and ranking risks, it was observed that adjustment for an individual’s sensitivity to that risk was necessary (e.g., the elderly and young children might be considered to be at higher risk than healthy adults), and also depended, in part, on an individual’s knowledge (e.g., awareness of the hazard and threat posed to health) and habits.

2.2 Tools Available for Comprehensive Home Assessment

In general, fully comprehensive tools for the overall assessment of home health (especially tools that are based on quantitative methods) do not appear to be well-developed or widely available, although some have attempted to update or develop more comprehensive home assessment tools in light of recent findings on the importance and breadth of residential hazards.

Many of the available tools are checklist-type tools for guiding visual inspections of homes or environmental sampling guidance. These include tools which are fairly focused on a narrow range of risks, while others attempt to more broadly assess a number of important home health hazards.

2.2.1 Comprehensive Assessments Focused on Specific Health Outcomes

Several assessment tools focused on specific outcomes have been developed, such as the home environmental assessment model focused on asthma developed as part of the Master Home Environmentalist (MHE) Program of the American Lung Association (Primomo, 2000). This program, which targeted homes where asthmatic children lived, included training volunteers to recognize asthma-related home health hazards and low-cost methods to reduce risks. Aspects of homes that were assessed included condition of ventilation systems and ducts, furnace filters, general cleaning habits, refrigerator drip pans, carpeting, and bedding covers. In a preliminary assessment of the program, which was based on occupant surveys, results showed that 75% of families felt the home environmental assessment improved their child's asthma (Primomo, 2000).

2.2.2 Comprehensive Assessments Assessing Hazards for Multiple Outcomes

HUD has developed a comprehensive "Healthy Homes Checklist" that is available on the HHI website¹ as a 12-page questionnaire for the family on a variety of health conditions. It includes a house structure and other assessment forms for each room of the house. Potential risk factors covered include biological hazards (e.g., allergens, molds), chemical hazards (e.g., pesticides, lead), structural hazards (e.g., excess moisture, poor ventilation), and behavioral hazards (e.g., poor safety practices, cigarette smoking). The Community Environmental Health Resource Center (CEHRC) has posted guidance on its website² that includes information on how to conduct (or obtain professionally) individual home assessments for lead, carbon monoxide, cockroaches, mold and moisture, and radon, as well as guidance on how to conduct a home safety visual survey and interpret sampling results reports.

In a more developed tool that attempts to use this sort of home assessment data to quantitatively rank home health, Great Britain's Department of the Environment, Transport and

¹ HUD Healthy Home Checklist http://www.hud.gov/offices/lead/hhi/4B_Boston_HHI_Checklist.pdf

² CEHRC guidance on home hazard assessment <http://www.cehrc.org/tools/index.cfm>

the Regions commissioned the development in 1998 of a new Housing Health and Safety Rating System (HHSRS)³ to replace the existing Housing Fitness Standard, which had been criticized for overlooking some of the most serious health and safety hazards in the housing stock. The new HHSRS, which was completed and released in 2000, includes risk factors such as toxic exposures (e.g., lead, radon, CO, consumer products), mold and moisture, HVAC and temperature issues, sanitary conditions and pests, and injury hazards, as well as several psychological factors such as safety from intruders and noise pollution. The tool is designed to be capable of evaluating individual risks to health and safety, as well as ranking both dwellings and housing condition according to the seriousness of the threat posed (Office of the Deputy Prime Minister, 2000).

The National Center for Healthy Housing website provides a more complete list of healthy housing assessment tools⁴. Over 40 tools are listed, along with information about the hazards they cover and how to access them.

3.0 CURRENT METHODS AND MODELS FOR ASSESSING INDIVIDUAL RESIDENTIAL HAZARDS

Generally, assessment of individual residential hazards involves one or all of the following:

1. Visual inspection to detect housing characteristics, such as water damage or structural deficiencies, that indicate a potential health hazard;
2. Occupant surveys to detect symptoms or behavioral patterns indicative of a hazard and to determine educational needs; or
3. Sampling of representative environmental media in the home (most commonly dust or air), quantification of a hazardous substance in the sample, and comparison to some threshold level or standard. The media sampled and methods of analysis largely depend on the characteristics (e.g., volatility or particle size) of the substance.

An overview of different assessment strategies, as related to selected home hazards, is presented in Table 1.

³ Great Britain's HHSRS <http://www.odpm.gov.uk/index.asp?id=1152820>

⁴ NCHH List of Healthy Housing Assessment Tools

http://www.centerforhealthyhousing.org/html/healthy_housing_assessment_tool.html

Table 1. Overview of Assessment Strategy Options for Selected Residential Hazards

Residential Hazard	Assessment Strategy			
	Visual Inspection	Occupant Survey	Dust Sampling	Air Sampling
Biological Hazards				
Dust mite allergens	(see excess moisture)		X ¹	x
Cockroach allergens	(see structural hazards)	X	X ¹	X
Pet allergens		X	X ²	X ²
Molds	(see excess moisture)	X ³	X ²	X ²
Bacterial toxins	(see excess moisture)		X	X
Chemical Hazards				
Pesticides		X ⁴	X ²	X ²
Carbon monoxide	X	X ⁵		X
Other airborne pollutants (e.g., VOCs, formaldehyde)		X ⁴		X
Other particulate phase pollutants (e.g., lead)			X	
Structural Hazards				
Structural defects	X	X ³		
Excess moisture	X	X ³		
Poor ventilation	X			
Unhygienic conditions	X			
Behavioral Hazards				
Cigarette smoking / ETS		X		X
Poor safety practices (e.g., not childproofing, no smoke alarms)	X	X		
Lack of supervision of children		X		
Unsafe use of products	X	X ⁴		
Personal/consumer product choices		X ⁴		
Other				
Lack of safety devices (safety gates, locks, detectors)	X	X		
Lack of professional inspection (e.g., of gas appliances)		X		
Lack of safety education		X		

¹ Substance primarily found in settled dust; airborne with dust disturbance.

² Substance may be found in high levels in both settled dust and in air.

³ Occupant survey can provide information on events, such as past sewer backups, plumbing leaks, water intrusion and surface mold that may no longer be apparent in a visual inspection.

⁴ Survey regarding consumer product choices.

⁵ Occupant survey can provide information on behavior that may influence CO levels, such as using a gas oven for heating or running a car in an attached garage.

Sections that follow briefly discuss current uses of visual inspections and occupant surveys for assessing residential hazards, as well as current methods for collection and analysis of environmental samples.

3.1 Visual Inspections and Occupant Surveys

Visual methods of environmental assessment and occupant surveys are most frequently used to assess physical conditions in the home (e.g., structural fall hazards, lack of safety equipment), moisture hazards (e.g., water leaks, condensation), combustion appliance hazards (e.g., improperly vented appliances), and home hygiene-related hazards (e.g., conditions promoting cockroach infestations). In addition, visual inspection and surveys may be used to assess housing conditions related to asthma, behavioral hazards (e.g., improper use of appliances, not following safety practices), and hazards associated with toxics and products that involve consumer choice. Visual inspection can also be used to assess the “cleanability” of surfaces in the home, which is related to how effectively surface contamination can be removed by the occupant’s routine cleaning.

In a report prepared for HUD’s Healthy Homes Initiative Peer Review: Unintentional Injury Prevention (Katcher, unpublished), home visitation was cited as one of the best ways to assess and address multiple injury hazards in the home, including initial home hazard inspections, customized interventions and resident education, and customized follow-up hazard inspection. Home visits for injury could be combined with other interventions (e.g., public health nurse visits, weatherization visits). Katcher estimates that the additional cost per visit of this add-on for injury assessment would be approximately \$100/visit.

Comparability of visual inspection results, self-reported measures from occupant surveys, and environmental sampling data is discussed in section 3.4.6 of this report.

3.1.1 Visual and Survey Assessment of Home Physical Conditions

Common points for home inspection for structural or physical deficiencies in a residence, such as those associated with certain injury risks, lack of safety devices, pest infestations, or moisture problems, are listed below.

3.1.1.1 Structural Hazards. Common points for home inspection regarding structure-related fall injuries include: handrails and lights on staircases, stairway design and disrepair, general lighting in home, and uneven floors. Structural deterioration may also lead to access points for pests to enter the home. The use of caulking, sealants, weather stripping, screens, and the installation of floor drains can help prevent pests from entering the home. In addition, as discussed in Section 3.1.2, structural deficiencies may be tied to moisture-related indoor health hazards, such as mold or certain allergen exposures, because many moisture problems in homes are due to structural problems.

3.1.1.2 Lack of Safety Devices. Home inspections should also include a check for the presence and use of recommended devices for the prevention of injuries, including:

- **Safety devices for the prevention of burns and deaths associated with fire and electrocution**, such as smoke alarms, fire extinguishers, home sprinklers, escape ladders, anti-scald devices for showers and sinks, safety covers for outlets, and ground circuit interrupters).
 - *Smoke alarms.* According to the U.S. Consumer Product Safety Commission (CPSC) (as cited in NSC, 2000), of the homes containing at least one smoke alarm, one of every five had no functioning alarm. The CPSC also found that 25% of all U.S. households had no smoke alarms or only non-functioning smoke alarms. Common causes for non-functioning smoke alarms include: a disconnected power source, a dead or missing battery, improper installation, or improper placement of the alarm. At least one smoke alarm should be installed on every floor of the home, including the basement, and outside each sleeping area. Because smoke rises, alarms should be mounted high on walls or ceilings, away from windows, doors, or forced-air registers where drafts could interfere with their operation.
 - *Fire Extinguishers.* Fire extinguishers can be used to put out small fires in the home. However, extinguishers must be checked periodically to ensure they are properly charged, and occupants must be trained on how to use a fire extinguisher effectively.
 - *Home Sprinklers.* The installation of home fire sprinklers is advocated by both the U.S. Fire Administration (USFA)⁵ and the National Fire Protection Associations (NFPA), but is often overlooked as an effective strategy for preventing deaths in house fires.
 - *Anti-Scald Devices and Thermostats in Water Heaters.* As of the late 1980s, water heater manufacturers have voluntarily agreed to preset all electric water-heater thermometers to 120°F (Dowd, 1999). However, because thermostats in water heaters can sometimes be inaccurate (especially in the case of older water heaters), parents are advised to measure hot water temperatures using a thermometer, and if necessary, lower the temperature so that it does not exceed 125°F to 130°F, where the likelihood of scald injury increases (Dowd, 1999; Schieber et al., 2000).
 - *Safety covers for outlets.* According to the Consumer Product Safety Commission, an estimated 1,300 electric shock and burn injuries are treated in the emergency room each year as a result of children inserting metal objects into electrical receptacle outlets. Outlet covers that are difficult for children to remove and large enough not to become a choking hazard are designed to help protect children from injury.
 - *Ground fault circuit interrupters (GFCI) and Arc Fault Circuit Interrupters (AFCI).* GFCIs are designed to sense disruptions in electrical current, turn off power to the affected circuit, and prevent the delivery of a lethal dose of

⁵ <http://www.usfa.fema.gov/safety/sprinklers/>

electricity. Local building codes generally require the installation of GFCIs in rooms with water sources, such as kitchens and bathrooms. AFCIs work by responding to early arcing and sparking conditions in home wiring to prohibit or reduce potential electrical fires from happening. The National Electrical Code, a widely-adopted model code for electrical wiring, has required AFCIs for bedroom circuits in all new residential construction since January 2002.

- **Devices to prevent falls.** These include access to grab bars and non-slip surfaces in the bathroom (to protect the elderly), non-slip backing on rugs, and safety gates to block stairs and dangerous areas, and window guards to prevent falling from windows (to protect children).
- **Poisoning prevention devices.** These include safety locks on poison storage cabinets and CO alarms. In addition to checking for the presence of functioning smoke and CO alarms, home assessments should evaluate the working condition and placement of these devices.
- **Gun Safety Devices.** These include lockable gun storage safes and gun locks.

3.1.2 Visual and Survey Assessment of Moisture and Mold Problems

High humidity levels and excess dampness have clearly been associated with mold growth, as well as increased levels of some environmental allergens, such as those produced by dust mites. Visual inspection for dampness, observable mold growth, and detection of musty odors, often obtained from occupant questionnaires, are the most frequently used methods to assess the potential for indoor mold exposure. Visual observation of mold growth, however, is limited by the fact that fungi are microscopic and therefore a mold problem may not be apparent until growth is extensive. In some cases, destructive sampling (e.g., the removal of a section of wallboard) is required to assess the extent of fungal contamination (Dillon et al., 1999). A device called a boroscope, which employs fiber optic technology to make observations in building cavities by inserting the instrument through a small hole drilled in materials such as wall board, can be used by home inspectors to facilitate assessment of hidden mold damage in a fairly non-destructive manner (Greenberg, personal communication). Although direct observation of visible fungal growth is usually sufficient to warrant a recommendation for mitigation, further air or source sampling (discussed later in Section 3.2) may be conducted for documentation purposes and to record the types of fungi that predominate (Burge and Otten, 1999).

Housing features that can increase moisture levels and growth of mold include poor ventilation, water leakage or flooding, and excess production or condensation of water in the house created by items such as humidifiers and unvented clothes dryers (Lawton et al., 1998; Gravesen et al., 1999). Many moisture problems in homes are due to structural deficiencies. Common points of inspection for buildings with dampness problems include: rain leaks through roofs and around windows; surface and groundwater leaks from poorly designed or clogged rain gutters and footing drains, basement design problems; plumbing leaks; and stagnant water in appliances (e.g., dehumidifiers, dishwashers, refrigerator drip pans, and condensing coils and drip pans in HVAC systems). In addition, assessment is also conducted for water vapor migration and condensation problems, including: uneven indoor temperatures, poor air circulation, air

conditioning systems, soil air entry into basements, contact of humid unconditioned air with cooled interior surfaces, and poor insulation on indoor chilled surfaces such as chilled water lines. Portable, hand-held moisture meters may also be useful in qualitative home assessments to aid in pinpointing areas of potential biological growth that may not be otherwise obvious during a visual inspection (ACGIH, 1999; Dillon et al., 2005).

Basements are likely to have higher mold concentrations than other indoor areas, especially in the winter (Ren et al., 1999). Li and Kendrick (1995) investigated 15 homes in Ontario and found that overall fungal levels (as assessed by counting spores in environmental samples) were highest in living rooms, followed by family rooms, kitchens, bathrooms, and bedrooms. Also in this study, it was observed that fungal levels increased with the presence of damp conditions and carpets, and decreased where forced-air heating systems, dehumidifiers, air filters, and air conditioners were present. Douwes et al. (1999) also found that fungal levels, as assessed by measurement of extracellular polysaccharide (EPS) fungal cell wall components from *Aspergillus* and *Penicillium* species (EPS-*Asp/Pen*), were highest in living room floor dust. In addition, EPS-*Asp/Pen* levels were 2 to 3 times higher on carpeted floors than on smooth floors, and this was confirmed by another study that adjusted for repeated measures (Chew et al., 2001). However, Ren et al. (2001) observed that surrogate measures of fungal presence in the home, such as damp spots, water damage, or leakage, as reported by household questionnaires, were not significantly and consistently related to the presence of culturable fungi measured in indoor air. Others, however, have had more success (Park et al., 2004; Mahooti-Brooks et al., 2004). Of note, geographic differences in home furnishings and climate should be considered when evaluating home characteristics and concentrations of fungi in air or dust samples (Chew et al., 2003).

Several studies have characterized mold in homes without significant moisture problems or visual mold growth (Chew et al., 2003; Gots et al., 2003; Su et al., 2001; Solomon, 1975; Ren et al., 1999; and Horner et al., 2004). Horner et al. (2004) reported the results of one such HUD-funded study that was conducted in 50 post-1945 detached single family homes in metropolitan Atlanta, Georgia. Indoor and outdoor air and interior settled dust samples were collected in summer and winter and culturable fungi were counted and identified. Although higher airborne mold concentrations were found in the indoor and outdoor samples collected in the summer, the indoor samples collected did not differ by rankings of mold type prevalence or abundance with outdoor samples. Water indicator fungi (*Chaetomium*, *Ulocladium*, and *Stachybotrys*) were identified in only 3% of the settled dust samples plated out on two different types of media. The researchers also reported that “leaf surface fungi” (e.g., *Cladosporium*, *Alternaria*, *Epicoccum*, and *Curvularia*) represented > 20% of the total colonies in at least 85% of the settled dust samples (thus, replicate dust samples with < 20% of colonies from leaf surface fungi may be indicative of a mold/moisture problem).

A variety of different protocols exist for assessing water damage in homes; for example, a visual assessment tool for inspecting homes for evidence of mold and moisture has been developed for Cleveland, Ohio, by the Cuyahoga County (Ohio) Board of Health for use in HUD-sponsored research (Dillon et al., 1999; EHW, 2004). An overview of additional techniques and issues of concern in conducting visual assessments of homes for mold

contamination is presented in *Bioaerosols: Assessment and Control* (ACGIH, 1999; see Chapter 4, “The Building Walkthrough”), or via the New York City Department of Health Guidelines on Assessment and Remediation of Fungi in Indoor Environments⁶. Chapter 3 of the Institute of Medicine report, *Damp Indoor Spaces and Health*, provides a list of questions used to define dampness used in 25 epidemiological studies (IOM, 2004). For large-scale assessments, e.g., in multifamily buildings, a sophisticated visual and olfactory inspection tool for moisture and mold developed by a NIOSH team may be useful (Park et al., 2004).

3.1.3 Visual and Survey Assessment of Combustion Appliance Related Hazards

Inadequately vented malfunctioning, or improperly operated combustion appliances and engines used in or around the home can potentially contribute to increased levels of numerous substances of health concern in indoor air, including toxic gases (e.g., nitrogen oxides, sulfur oxides, VOCs, and carbon monoxide) and airborne particulates. Carbon monoxide poisoning is the most common cause of acute poisoning by inhaled gases in residential situations (NSC, 2000). Certain appliances can also contribute to increased moisture problems in the home. Preventing combustion exposures requires routine periodic maintenance to ensure that the fumes from appliances are adequately vented, as well as responsible operation of combustion appliances and motor vehicles by home occupants.

Occupant surveys and visual inspection can be used to evaluate housing conditions, as well as behavioral factors, that contribute to combustion-related residential hazards.

Due to the intermittent nature of many problems associated with combustion appliances, occupant surveys and visual inspections are an extremely important tool in evaluating hazardous housing conditions and behaviors that could potentially contribute to combustion gas exposure. Many of these hazards may not readily be apparent from direct sampling and analysis of indoor air on a one-time or limited sampling schedule. For example, although air sampling at the time of investigation may not show any air toxics at a level of concern, observed housing conditions such as the presence of an attached garage, an improperly installed furnace ventilation system, or visual evidence of the backdrafting of combustion gases (e.g., soot, scorched surfaces, and melted fittings near the vent) may indicate the potential for or periodic build-up of combustion gases to dangerous levels in the home. Surveys and inspections are also used to identify inappropriate use of equipment (e.g., cooking ranges used for heating, space heaters in violation of codes, etc.) or other occupant behavior that might affect CO exposure, such as idling a vehicle or operating a generator in an attached garage.

Common points of home inspection for point sources of combustion gases, particulates, or moisture in homes include: exhaust ventilation for furnaces, water heaters, dryers, kitchen ranges, bathrooms, fireplaces, and general dilution ventilation in the home. The American Society for Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) publishes consensus guidelines for ventilation requirements. Common household appliances that may be sources of combustion gases when inadequately vented or malfunctioning include vented gas,

⁶ NYC Department of Health mold assessment guidelines www.ci.nyc.ny.us/html/doh/html/epi/moldrpt1.shtml

oil, and wood burning appliances such as water heaters, furnaces and boilers, dryers, fireplaces and woodstoves, as well as unvented appliances like space heaters, cooking ranges, and ovens. Combustion gases in the indoor environment from vented combustion appliances (furnaces, hot water heaters, and gas clothes dryers) are generally negligible unless the unit is malfunctioning, leaking, or backdrafting (USEPA, 2000). According to an U.S. EPA report, because unvented gas cooking ranges and ovens are used intermittently for cooking purposes, it is not likely that their use would result in substantial increases in CO over long periods of time, except possibly in households where gas ovens are being used improperly as a primary or secondary source of heat (USEPA, 2000). Other unvented combustion sources can also be a hazard when used improperly, such as charcoal grills, hibachis, or gasoline-powered engines or tools (e.g., portable generators, pumps, or power washers) used in enclosed or partially enclosed environments, or gasoline-powered vehicles started or left idling in attached garages. CO can potentially be drawn into a house from any combustion source being operated in an attached garage, including motor vehicles, lawn mowers, or grills. Even if the garage doors are open, CO can seep into the house, particularly in situations where backdrafting is occurring.

Numerous organizations, such as the CPSC and the Canada Mortgage and Housing Corporation (CMHC), as well as several commercial organizations, provide guidance on important home checkpoints for conducting overall CO investigations in the home. In November 2003, the CPSC made the following guidance available online: “Responding to Residential Carbon Monoxide Incidents: Guidelines for Fire and Other Emergency-Response Personnel.”⁷ Other examples include the Building Performance Institute’s (BPI) draft protocol, “Carbon Monoxide Analyst Protocol,”⁸ and R.J. Karg Associates’ “Chicago Protocol: A Protocol for the Testing of Carbon Monoxide Emissions.”⁹

Typical appliance (e.g., furnace, stove, or fireplace) problems leading to the release of CO in homes that may be difficult for a homeowner to identify include: cracked heat exchangers; insufficient air for proper combustion; defective/blocked flues; and maladjusted burners. According to the CPSC, yearly inspections of homes by a professional (e.g., heating contractor or Gas Company) should include a careful look at the following sources of CO:

- **Furnaces, water heaters, boilers, and stoves.** If they burn natural gas, heating oil, wood, or other kinds of fuel, these appliances are potential sources of CO and other toxic combustion gases.
- **Chimneys, flues, and vents.** Flues and chimneys should be inspected before each heating season for leakage and for blockage by creosote or debris. Creosote buildup or leakage could cause black stains on the outside of the chimney or flue. These stains can mean that pollutants are leaking into the house. All vents to furnaces, water heaters, or boilers should be checked to make sure they are not blocked, loose, or disconnected. Snow and ice also create the potential for vent blockages. Owners and residents should

⁷ www.cpsc.gov/library/foia/foia04/os/resident.pdf

⁸ <http://home.att.net/~cobusters1/coprocol.htm>

⁹ <http://www.karg.com/CO%20Protocol.htm>

know where all of their vents exhaust and be aware of those areas where heavy snow or ice can impact proper operation.

- **Improper ventilation.** Fuel burning appliances require adequate ventilation. A supply of fresh air is important to help carry pollutants up the chimney, stovepipe, or flue and is necessary for the complete combustion of any fuel.
- **High Temperature Plastic Venting (HTPV) pipes.** Consumers should have the vent pipes on their natural gas or propane heating systems inspected for the presence of HTPV pipes. The HTPV pipes could crack or separate at the joints and leak CO into the home. In 1998, virtually the entire furnace and boiler industry together with the manufacturers of high-temperature plastic vent (HTPV) pipes joined with the CPSC to announce a vent pipe recall program.

Another target area for professional assessment is the potential for backdrafting problems, particularly in tightly-sealed homes. Backdrafting occurs when the air pressure within a home is lower than the air pressure outside, a phenomenon known as house depressurization. When these conditions exist, flue combustion gasses (CO, CO₂, NO₂, etc.) can reverse direction, spilling into the living area of a home instead of traveling up a vent or chimney. Visual evidence of the backdrafting of combustion gases includes soot, scorched surfaces, and melted fittings near the vent (CMHC, 1998). If a backdrafting problem is suspected, a professional heat contractor should check the house and heating systems. Small temperature-sensitive strips called “Backdraft Indicators” can be attached to the draft diverter (which regulates the flow of air in HVAC systems) to detect backdrafting of exhaust gases (ISU Extension Publication, 1996). A chimney flow test may also be conducted by holding a smoke indicator (such as an incense stick) near the draft hood of a gas furnace or water heater, and watching the direction of smoke movement at the draft hood or damper, both with and without exhaust fans and other exhaust equipment in the house turned on (CMHC, Combustion Gases in Your Home online). If the smoke moves into the house, there may be a spillage problem.

Various guidance documents with suggested protocols for conducting safety testing of combustion appliances, including spillage and CO emissions, have been developed, including:

- ASTM Standard E1998-02, “Standard Guide for Assessing Depressurization-Induced Backdrafting and Spillage from Vented Combustion Appliances”;
- Section H of the National Fuel Gas Code (ANSI Z223.1/NFPA 54);
- ASHRAE 62.2 Appendix A, Checking the Venting of Combustion Appliances;
- Canada General Standards Board- 51.71-95, “The Spillage Test Method to Determine The Potential for Pressure Induced Spillage from Vented, Fuel-fired, Space Heating Appliances, Water Heaters and Fireplaces”; and
- Iowa State University, Agricultural and Biosystems Engineering Extension, provides numerous factsheets on combustion appliance inspection, as well as other information on CO hazards (see, for example, “Carbon Monoxide Poisoning - Checking for Complete Combustion ISU Extension Pub # AEN-175 available at http://www.abe.iastate.edu/human_house/aen175.asp).

Along with regular inspection of combustion appliances, properly working CO alarms can provide home occupants with warning when indoor CO levels reach dangerous levels. For example, in a study of unintentional CO poisoning deaths in New Mexico (1980 through 1995), Yoon et al. (1998) found that 49% of residential CO deaths occurred when the occupants were sleeping and estimated that (of the victims without the presence of alcohol in their blood) approximately half (78) of the deaths could have been prevented if audible CO alarms were used. The U.S. CPSC recommends that consumers purchase home alarms that meet specifications established by Underwriters Laboratories (UL) 2034 standard for CO detectors/alarms, “Single and Multiple Station Carbon Monoxide Detectors” (UL, 2002) or the Canadian Standards Association CAN/CSA 6.19-01, and the previous International Approval Services IAS 6-96. All three organizations are well respected standards developers and their standards are equally acceptable to the CPSC staff. CPSC recommends that all homes have one CO alarm that meets the requirements of UL 2034, IAS 6-96, or CAN 6-19-01 installed in the hallway near every separate sleeping area of the home.

3.1.4 Visual and Survey Assessment of Pesticide Hazards

From a public health program perspective, simple, non-invasive methods to assess potential pesticide exposures in the home include inventory surveys of pesticides stored throughout a home and garage and recall questionnaires about pesticide use and frequency of application (Adgate et al., 2000). These methods are lower in cost than conventional sampling and chemical analyses and point to the general prevalence of pesticides use in and around the home, and thus the potential for an exposure event to occur. However, the inventory approach will miss a product that has been used completely and no container remains for counting. Surveys are also often flawed because personal recall of pesticide use has low validity generally, and recall of specific product use is quite poor (Gordon et al., 1999). Some of this is due to the very nature of insecticide use indoors – products are readily available in convenient-to-use containers, and use is sporadic and rapid. In addition, individual activity factors, for the applicator, the child, other family members, and even pets, can have dramatic impacts on exposure. An individual’s attitude and perception of risk related to pesticide use can also influence information obtained in questionnaires and potentially result in underreporting, especially when questions used to obtain information are limited in scope (Nieuwenhuijsen et al., 2005).

Very limited information is available on how well pesticide exposure information obtained from questionnaires corresponds with data collected from environmental samples taken in the home. Sexton et al. (2003) found that telephone screening and questionnaires were inadequate predictors of households exposed to higher levels of target pesticides, possibly due to incongruity between the general questions asked on the survey and the far more specific pesticide measurements taken in sample homes. However, Colt et al. (2004) found information gathered from the use of detailed questionnaires that included visual aids and focused on the types of pests treated, who applied the pesticide, how often the pesticide was applied, and longer time frames of interest, correlated well with the types of pesticides found in vacuum bag samples. In addition, authors suggest that detailed questionnaires can be useful in capturing pesticides used in the home prior to the installation of carpets. Therefore, when used in

conjunction with environmental sampling, questionnaires can provide additional useful information that may not otherwise be captured.

3.1.5 Visual and Survey Assessment of Behavioral Hazards

There are a number of common activities and consumer products that, when conducted or used in an unsafe manner, can produce indoor air contaminants, unintentional poisoning risk, or other injury risk. For example, inappropriate use of combustion appliances can result in increased levels of CO in indoor environments. Choice of products and protocols for activities such as cleaning, cooking, pest control, and renovation (paints, varnishes, wall and floor coverings, demolition, etc.) may involve avoidable hazards if alternate (e.g., less toxic) products are used and safety precautions (e.g., adequate ventilation) are practiced. Simple behavior modifications such as removal of clutter and loose throw rugs in walkways, use of appropriate footwear, and improved lighting have the potential to reduce fall hazards in the home.

The lack of safety devices in the home is also a primarily behavior-controlled factor in injury-related hazards. Potential points of inspection for safety devices in a home include: smoke alarms, CO detectors, fire extinguishers, ground fault circuit interrupters, and, if children are present, safety gates, window guards, outlet covers, and anti-scald devices on water faucets.

Hygiene-related health hazards in the home include microorganisms (e.g., bacteria, mold), toxicants (bacterial, fungal, or chemical), and allergens (Jones, 1998). In addition, hygiene-related housing conditions (e.g., presence of standing water or open food sources) have been shown to promote cockroach and rodent infestations (Bradman et al., 2005).

3.1.5.1 Behaviors Affecting Risk of CO exposure. Surveys and visual inspection can provide valuable insight into home occupant behaviors that can potentially affect the risk of CO exposure. For example, surveys and inspections may be used to identify inappropriate use of equipment by occupants (e.g. cooking ranges for heating, space heaters in violation of codes, etc.) or problems with equipment, chimneys, flues, vents, or ventilation.

Commonly recommended points for homeowner education regarding CO hazards and behavior include:

- Proper use, cleaning, and maintenance of gas ovens (e.g., making sure secondary air ports are not blocked by aluminum foil, never using stove tops or ovens to heat your home).
- Proper use of propane, natural gas or charcoal barbecue grills, portable generators, or any gasoline-powered tool (i.e., never use indoors or in an attached garage).
- Safety where attached garages are present (e.g., never starting a vehicle in a closed garage, pulling the car out immediately onto the driveway, then closing the garage door to prevent exhaust fumes from being drawn into the house).
- The importance of regularly checking the clothes dryer and other ductwork and outside vent covers for blockages such as lint, snow, or overgrown outdoor plants.

- Information on the proper use, placement, and maintenance of CO alarms.
- Education about the need to have all gas or other fuel-burning appliances inspected and maintained regularly by a professional, chimney flues cleaned regularly, etc.

3.1.5.2 Survey of Occupant Knowledge of Safety Procedures and Devices. As discussed previously under “Structural Injury Hazards,” a home safety assessment may include a survey on homeowner knowledge of devices to prevent burns and deaths associated with fire, including smoke alarms, fire extinguishers, home sprinklers, escape ladders, anti-scald devices for showers and sinks, safety covers for outlets, and ground circuit interrupters. The survey may also include assessment of other risk behaviors, for example: leaving children unsupervised, not locking up poisons and firearms, smoking in the home, not using childproof lighters, not using flame retardant sleepwear, lack of practiced fire escape routes, placing space heaters near flammable materials, and not using low thermostat settings for water heaters.

Commonly recommended points for homeowner education regarding injury hazards and behavior include:

- **Fire and Burn Education.** Programs funded by the National Fire Protection Association and public fire departments help save lives by teaching the public how to prevent fires and how to react during fires. Fire prevention education includes lessons on potential home fire hazards (e.g., smoking in bed, poorly maintained furnaces and chimneys), how to “stop, drop, and roll,” the use and maintenance of smoke alarms, fire extinguishers, home sprinklers, and thermostats in water heaters (see Section 3.1.1.2), the danger in leaving children unattended, keeping matches and lighters away from children, and developing a family escape plan that includes multiple escape routes with unblocked exits or quick-release devices (for bars and locks), fire drills, and a designated safe meeting place outside.
- **Falls.** Prevention measures involve modifying behavior or home structure. For parents, these include actions such as securely strapping children in high chairs, moving cribs away from windows, supervising children, child-proofing homes (e.g., use of safety gates and installing window bars), and repairing structural defects.
- **Poisoning.** Beyond the CO-poisoning hazards discussed in Section 3.1.4.1 above, the primary residential hazards associated with other types of unintentional poisonings are behavior (e.g., not locking up dangerous substances, improper use of products such as cleaners and pesticides, accidental or improper drug ingestion), exposure to lead-based paint (e.g., dust from sanding lead-based paint, peeling paint chips), and lack of child-proof storage for toxic substances. Preventive measures include mitigating lead hazards, installing safety locks on cabinets, locking up medicines and dangerous substances, buying less toxic consumer products, and taking medicines as prescribed.
- **Choking.** Methods to prevent choking include keeping dangerous objects away from children and education on the Heimlich maneuver and CPR, the appropriate size of toy

parts for small children, and the appropriate size of food for small children and the elderly.

- **Drowning.** Training in cardiopulmonary resuscitation (CPR) is strongly recommended for owners of swimming pools (Baker et al., 1992). A study of low-income urban families found that 89 percent of children aged 35 to 59 months and 6 percent of those younger than 3 years old sometimes bathed without adult supervision (Santer and Stocking, 1991). Prevention of drownings and near-drownings requires education concerning the importance of supervising children, particularly during bathing and while five-gallon buckets are in use. The CPSC offers three free publications consumers can use to help prevent child drowning: "Safety Barrier Guidelines for Pools," "How to Plan for the Unexpected – Preventing Child Drownings," and "Guidelines for Entrapment Hazards: Making Pools and Spas Safer." Copies of these publications can be obtained at CPSC's website at www.cpsc.gov.
- **Suffocation and Strangulation.** Prevention requires safe sleep and play environments for children. Cribs slats should be less than 2 ^{3/8} inches apart; mattresses and sheets should be well-fitting; storage and toy chests should have safety lids; window cords should be tied up, and plastic bags should be kept out of reach of children. Parents can also further reduce suffocation hazards in young children by following CPSC guidelines to avoid placing babies to sleep on adult beds (CPSC, 2004a), soft bedding for babies (CPSC, 2004b), ill-fitting crib sheets (CPSC, 2004c), and improperly fitting crib mattresses (CPSC, 2004d).
- **Firearm Safety.** Following safe gun storage practices (i.e., keeping firearms locked and unloaded and ammunition locked and stored separately) minimizes the risk of firearm-related injury.

3.1.6 Visual and Survey Assessment of Asthma-Related Hazards

While the discussion in this report focuses on quantitative methods for assessing residential allergens and other potential asthma trigger, other methods such as lower cost visual inspection or questionnaires or checklists can also provide a qualitative assessment of the potential asthma hazard in a home. Visual measures such as dampness, visible mold growth, signs of cockroach or rodent activity, the presence of pets, the presence and condition of upholstery and carpets, the presence of sources of CO or VOCs, and general cleanliness, can all be used to identify particularly obvious sources of potential asthma exacerbation.

Chew et al. (1998) evaluated the usefulness of a home characteristics questionnaire in predicting indoor allergen levels and found that although certain home characteristics (such as smooth versus carpeted versus smooth floors) were significant predictors of increased allergen levels, home characteristics reporting was a relatively weak predictor of the absence of allergen. For example, in comparison to dust from smooth floors, dust from carpeted bedroom floors had 2.1 times the risk of having dust mite allergen at levels ≥ 10 $\mu\text{g/g}$; however, high levels of allergen were also measured in situations where no carpets were present. The authors

noted that relatively high levels of allergens can be present even in situations where general home characteristic would suggest otherwise (e.g., where beds were encased in plastic, no cats were present, no carpets were present, and no sign of cockroaches had been reported).

3.2 Collection of Environmental Samples

Collection of environmental samples of dust, air, mold, etc. allows for direct measurement of a wide range of hazard indicators such as allergens, molds, pesticides, and toxic substances. The advantage of this assessment method is that it provides a quantitative estimate of the hazardous substance. However, as can be seen from the history of lead risk assessment, the remaining challenge is the interpretation of the quantitative measures of the hazardous substance in the specific measured medium in terms of exposure and risk, especially given the fact that for many residential hazards, significant questions remain concerning risk factors and levels of concern.

3.2.1 Bulk and Surface Sampling: Dust and Other Solid Media

Dust sampling is commonly used to estimate environmental levels and hazard potential for allergens, lead, and various other toxic substances (e.g., pesticides) that are associated with particulate matter. Results are typically expressed as either concentration (units of weight of substance per weight of dust) or loading (units of weight of substance per unit of area sampled). Sampling of dust reservoirs is usually achieved using a suction device or wipe sampling. In residential investigations, hand-held vacuums with special filters are typically used.

Recently, Arbes et al. (2005) evaluated the feasibility of having subjects collect their own home dust samples. Results of the study, which compared allergen concentrations between subject- and technician-collected samples (n=102), indicated that correlations between subject- and technician-collected samples were strong for concentrations of cat allergen and dust mite allergen, although subjects collected lighter dust weight samples. The authors concluded that, with some limitations, subject-collected dust sampling appears to be a valid and practical option for epidemiologic and clinical studies that report allergen concentration as a measure of exposure.

Sampling of dust reservoirs is usually achieved using either a suction device or wipe sampling. HUD has developed a recommended “Vacuum Dust Sample Collection Protocol for Allergens” for use by HUD Healthy Homes Initiative grantees (HUD, 2004a). The protocol is adapted from sampling methods used in the National Survey of Lead in Allergens in Housing and the Inner-City Asthma Study, and it is supported by a companion HUD document, “Background and Justification for a Vacuum Sampling Protocol for Allergens in Household Dust” (HUD, 2004b). These and other reports containing dust sampling methods are available on HUD’s website at http://www.hud.gov/offices/lead/techstudies/Allergen_Dust_Sample_Protocol.doc. A hand-held portable vacuum cleaner, electric powered, not battery operated, is recommended, with a filter, sleeve or thimble dust collection device. Most electric powered canister vacuum cleaners are essentially equivalent in their measurement of indoor allergens, but it is necessary

to choose a model that can accommodate the dust collection device that will be used (HUD, 2004a).

Various factors, including design of the vacuum collector, characteristics of the surface sampled (e.g., carpet vs. smooth floor, construction of the carpet, type of carpet fiber), and other environmental characteristics (e.g., relative humidity) have all been shown to affect the efficiency of vacuum dust collection (Wang et al., 1995; NAS, 2000). For example, Wang et al. (1995) observed that when collecting dust with a vacuum sampler from a shag carpet surface, lower relative humidity (e.g., around 20 percent, as would be encountered during a dry, cold season) increased the intensity of the electrostatic field on the carpet and thus significantly decreased the collection efficiency of the vacuum.

3.2.1.1 Allergens. An overview of sampling assessment strategies for selected residential asthma triggers (allergens) is summarized in Table 2. Indoor environments generally contain large reservoirs of allergens in settled dust accumulated in carpets, bedding, and upholstery. Depending on dust disturbing activity, only a very small amount is usually airborne at a given time (with the exception of cat and other animal allergens, which may also have relatively high airborne levels). The primary route of exposure to allergens is presumed to be inhalation of airborne particles. Reservoir levels are more reflective of an integrated chronic exposure rather than being markers for short-term exposures. Therefore, environmental assessment with regard to allergens has primarily involved measuring allergen levels in dust samples obtained from reservoir sources within the house. Bedroom concentrations are typically used as markers of allergen exposure because activity pattern analyses indicate that bedroom areas are where the majority of exposure usually occurs (NAS, 2000).

Table 2. Overview of Assessment Strategy Options for Selected Residential Asthma Triggers ¹

Residential Trigger	Assessment Strategy					
	Sampling		Analysis		Test Applicability	
	Method	Reliability	Method (units)	Quality assurance	Important Species	Data Obtained ²
Dust mite allergens	Dust sampling by vacuum	Spatially and temporally variable; most mites in settled dust	ELISA ³ (µg/g)	Accurate quantitation, sensitive	Dermatophagoides species and Blomia tropicalis	Allergen levels (Group 1 (Der p 1 * and Der f 1); Group 2 (Der p 2 and Der f 2); Blo t 5)
			ACLOTTEST® ⁴	Semi-quantitative (quicktest)	D. pteronyssinus and D. farinae	Detection of Group 2 mites sensitive to 0.5 µg/g dust
			Gold-based lateral flow test ⁵	Semi-quantitative, sensitive (quicktest)	D. pteronyssinus and D. farinae	Allergen levels (Der p 1 * and Der f 1)
	Air sampling with static or personal sampler	Spatially and temporally variable; also variable with disturbance	ELISA ³ (pg/m ³)	Accurate quantitation, sensitive	D. pteronyssinus	Allergen levels (Group 1 (Der p 1 * and Der f 1); Group 2 (Der p 2 and Der f 2); Blo t 5)
	Dust or air (sampled as above)	See above	Particle immunostaining	Extremely sensitive	D. pteronyssinus	Allergen levels (Der p 1* and Der p 2)
Cockroach allergens	Dust sampling by vacuum or air sampling with static or personal sampler	Spatially and temporally variable; most cockroach allergen in settled dust; air levels variable with disturbance	ELISA ³ (Units/g) (dust) ELISA ³ (Units/m ³) (air)	Accurate quantitation, sensitive	Blatella germanica and Periplaneta americana	Allergen levels (Bla g 1 and Bla g 2)
			Particle immunostaining	Extremely sensitive	Blatella germanica	Allergen levels (Bla g 1)
	Trapping		Cockroach counts		Nonselective	Estimates of cockroach population
Pet and rodent allergens	Dust sampling by vacuum or air	Spatially and temporally variable; variable with disturbance; high levels of pet allergen airborne	ELISA ³ (µg/g) (dust) ELISA ³ (pg/m ³) (air)	Accurate quantitation, sensitive	Felis domesticus, Canis familiaris, Mus musculus	Allergen levels (Fel d 1, Can f 1 *, Mus m 1, Rat n 1 (rat urine))
	Sampling with static or personal sampler		Particle immunostaining	Extremely sensitive	Canis familiaris and Felis domesticus	Allergen levels (Can f 1 * and Fel d 1)

¹ See text for references.

² Allergens listed in this column are those for which monoclonal antibodies are typically commercially available for immunoassay purposes (see INDOOR Biotechnologies website, <http://www.inbio.com/index.html>)

³ Quantitative differences between allergen standards are currently an important source of assay (ELISA) variability.

⁴ Additional information on ACLOTTEST® is available on the internet from the Allergy Buyers Club, <http://store.yahoo.com/allergybuyersclub/dustmitetestkit.html>.

⁵ Additional information on the gold-based lateral flow test is available from INDOOR Biotechnologies, Ltd. Rapid Test for Mite Allergens (RAPID) at http://www.inbio.com/Rapid_Test_Kit.html.

* Allergens with established WHO International reference preparations

Table 2. Overview of Assessment Strategy Options for Selected Residential Asthma Triggers ¹ (continued)

Residential Trigger	Assessment Strategy					
	Sampling		Analysis		Test Applicability	
	Method	Reliability	Method (units)	Quality assurance	Important Species	Data Obtained ²
Mold Allergens and Surrogate Mold Measures	Dust or surface sampling by vacuum, surface wipe, swab, or tape Bulk sampling of contaminated materials Air sampling with static or personal sampler *Also see Table 4 for additional pros/cons of the various types of mold sampling/assessment strategies	Spatially and temporally variable; air levels variable with disturbance	ELISA ³ (µg/g) or pg/m ³)	Not currently reliable for fungi (e.g., Alternaria counts must be very high)	Aspergillus, Alternaria, Cladosporium	Allergen levels (Asp f 1 and Alt a 1)
			Spore Count	Intact spores may not account for total allergen load	All (Aspergillus and Penicillium species difficult to identify)	Concentration of spores; spore identification
			Culture	Viable fungi may not account for total allergen load	All (may miss poorly competing species of low viability, e.g. Stachybotrys chartarum.)	Species identification; Estimates of fungal concentrations
			Chemical biomarkers (ergosterol, beta-D-glucan)	Good indicators of total biomass; cannot identify species	Not species specific: Components in all fungal hyphae and spores (as well as some algae and yeasts) Beta d-glucan is biologically active	Concentration of chemical biomarker; Estimates of fungal biomass
			Polymerase chain reaction (PCR) based technologies (i.e., genetic probes)	Accurate: Based on targeting species-specific sequences of DNA for the 130 species for which probes have been developed	Species specific, including but not limited to: Alternaria, Aspergillus, Cladosporium and Penicillium	Mold identification to the species level
			Particle immunostaining	Extremely sensitive	Alternaria	Allergen levels

¹ See text for references.

² Allergens listed in this column are those for which monoclonal antibodies are typically commercially available for immunoassay purposes (see INDOOR Biotechnologies website, <http://www.inbio.com/index.html>)

³ Quantitative differences between allergen standards are currently an important source of assay (ELISA) variability.

⁴ Additional information on ACLOTTEST® is available on the internet from the Allergy Buyers Club, <http://store.yahoo.com/allergybuyersclub/dustmitetestkit.html>.

⁵ Additional information on the gold-based lateral flow test is available from INDOOR Biotechnologies, Ltd. Rapid Test for Mite Allergens (RAPID) at http://www.inbio.com/Rapid_Test_Kit.html.

* Allergens with established WHO International reference preparations

For allergens associated with dust, it has been suggested that repeated sampling of dust over time gives better information about long-term exposures of the individual to allergens due to temporal variability (Hirsch et al., 1998). In addition, because it has been observed that concentrations of allergens in dust can vary significantly over short distances within a room, by convention, the sample with the highest allergen concentration is typically used as the measure of exposure (O'Meara and Tovey, 2000). Surfaces vary widely in amount of total dust from room to room or home to home. Therefore, when collecting samples of settled dust, it is advisable to record the area sampled in order to report results as concentration of allergen or other agent per unit of area (e.g., m²) as well as concentration per gram of dust.

Although sampling season has been shown to be a source of variation in cat allergen (possibly associated with fur shedding cycles or the time a pet spends indoors), mite, fungi, and cockroach allergen levels (due to seasonal changes in temperature and humidity) in household dust, the influence of other home characteristics can far outweigh the significance of seasonal variation (Chew et al., 1999; Flannigan, 1997). For example, Chew et al. (1999) observed that dust mite allergen concentrations were 1.9-2.4 times higher in the autumn than in the spring but that the levels in beds in single-dwelling houses were 19-31 times higher than in apartments, thus far outweighing the seasonal effects observed. In addition, a national survey of U.S. housing, conducted by HUD and the National Institute of Environmental Health Sciences in 1999/2000, found that older, low income housing had higher levels of important asthma triggers (dust mites, cockroach allergen, rodent allergen) and lead-based paint hazards (Arbes et al., 2003; Cohn et al. 2006; Jacobs et al., 2002).

House dust mite and cockroach allergen particles are typically relatively large in size (10-25 µm), and as such, tend to remain airborne for comparatively short periods of time (on the order of minutes). Therefore, because there is very little or no airborne dust mite or cockroach allergen in an undisturbed room, air sampling for these allergens is relatively uncommon. The currently accepted method for assessing dust mite and cockroach exposures is to measure (via assay, as discussed below) concentrations of allergens in dust samples collected by vacuuming, preferably in the bed or bedroom. Sampling locations may vary for cockroach allergens because they are usually found in greater concentrations (e.g., up to an order of magnitude) in kitchens and bathrooms due to the availability of food and water sources. Because cat and dog allergens are carried on smaller airborne particulates that remain suspended in the air for long periods of time, air sampling is often successfully used to assess these allergen levels for intervention studies.

In summary, the pros and cons of dust versus air sampling for allergens are presented in Table 3.

Table 3. Pros and Cons of Dust Versus Air Sampling for Allergens

Sampling method	Pros	Cons
Settled dust sampling	<ul style="list-style-type: none"> • Better indicator of time-integrated exposure. Less temporally variable. • Better indicator of exposure to house dust mite and cockroach allergens, because particles tend to remain airborne for relatively short time periods. • Sample collection is relatively fast, easy and inexpensive. 	<ul style="list-style-type: none"> • May be poor indicator of short-term exposures.
Air Sampling	<ul style="list-style-type: none"> • Captures inhalable particles. Better indicator of short-term exposure. • Allows fluctuations in exposure to be assessed over a week or a day. • Successfully used to assess cat and dog allergens, because particles remain airborne for relatively long time periods. • May be useful if it is suspected that ventilation systems are contaminated. 	<ul style="list-style-type: none"> • Airborne concentrations for many allergens are generally low, so samples encounter limits of analytical sensitivity. • Allergen levels in air vary with amount of disturbance. • To represent longer term exposure, a much larger number of samples must be collected. • May provide poor representation of exposure to house dust mite and cockroach allergens, because particles tend to remain airborne for relatively short time periods.

3.2.1.2 Mold and Bacterial Toxins (Endotoxins). Quantitative assessment of indoor molds generally involves sampling of a representative environmental medium in the home and quantification of the measure of interest (e.g., allergen concentration, total fungal biomass, or spore count). Air and dust sampling, as well as direct source sampling of mold colonies where visible mold growth is present, are used to estimate environmental levels of fungi. An overview of selected mold sampling strategies is provided in Table 4. However, current guidance generally discourages collecting and analysis of environmental samples for mold analysis in most situations (USEPA, 2001b; CDC, 2005). This is based on factors such as cost, the high variability in sampling results (both spatial and temporal variability), and the fact that remediation decisions are generally not based on sampling results. Significant residential mold problems can usually be identified from visual observation and/or the presence of odors. Situations where sampling might be conducted include those in which the source of the mold is unclear, litigation is involved, or to test a surface to document adequate cleaning or remediation. Note, however, that some experts recommend that sampling should not be used to verify adequacy of cleaning, because of the high risk of false negatives. In addition, standard methods for quantitative sampling of mold or models that would allow for estimates of inhalation or dermal exposure to molds from sampling results are not available (IOM, 2004; Dillon et al., 1999).

Table 4. Selected Mold Sampling Strategies¹

Type of Environmental Sample	Sampling Techniques	Advantages/ Disadvantages	Possible/Example Results
Bulk	- Remove section of building material (e.g., wallboard)	- Destructive technique	- Detection of past mold colonization or active growth
	- Vacuum or wipe larger area to collect loose bulk material (e.g., settled dust)	- Non-destructive - Dust can have inhibitors like salt which can limit growth of some fungal taxa - Spatially and temporally variable - Efficiency of bulk dust collection may be affected by environmental factors (see discussion below)	- Identification of surfaces/areas where previously airborne mold spores and fragments have settled and accumulated
Surface	- Press collection material (e.g., a contact plate or adhesive tape) against a surface - Wipe small area with a wetted swab, cloth, or filter - Vacuum sample of settled dust.	- Non-destructive - Spatially and temporally variable - Settled dust samples expected to be less temporally variable and be a better indicator of exposure over time.	- Detection of past mold colonization or active growth - Identification of surfaces/areas where previously airborne mold spores and fragments have settled and accumulated
Air	- Static sampler - Personal sampler - With HVAC off and on	- Useful if it is suspected that the ventilation systems are contaminated - Air levels are variable, especially with disturbance - Short-term air samples limit sensitivity	- Detection of mold contamination where the presence of mold is suspected but cannot be identified by a visual inspection or bulk sampling

¹ See text for references.

Source sampling methods of investigating mold contamination in homes include bulk and surface sampling. Generally, indoor environments contain large reservoirs of mold spores and hyphal fragments in settled dust and contaminated building materials, of which only a relatively small amount is airborne at a given time. Chew et al. (2003) reported that concentrations of fungi in settled dust generally correlate weakly with those in indoor air.

In bulk sampling techniques, portions of environmental materials (e.g., settled dust, sections of wallboard, pieces of duct lining, carpet segments, or return air filters) are collected and tested to determine if molds have colonized a material and are actively growing and to identify surfaces where previously airborne mold spores and fragments have settled and accumulated (Martyny et al., 1999). For fixed materials, bulk samples are cut or otherwise removed from the source; thus, this technique may be somewhat destructive. For loose materials, such as floor dust, bulk samples are typically collected using wipe sampling or a hand-held vacuum with a special filter. Factors affecting the efficiency of dust collection and standardized dust collection techniques are discussed at the beginning of section 3.2.1.

Surface sampling in mold contamination investigations may also be used when a less destructive technique than bulk sampling is desired. In general, surface sampling is typically accomplished by either pressing a collection material (e.g., a contact plate or adhesive tape)

against a surface, or by wiping an area with a wetted swab, cloth, or filter (Martyny et al., 1999). The size of a collected surface sample is generally much smaller than that of a bulk sample. An overview of procedures and advantages of various contact sampling techniques, including agar plate methods, adhesive tape sampling, and surface-wash sampling, is presented in *Bioaerosols: Assessment and Control* (ACGIH, 1999; see Chapter 12, “Source Sampling” by Martyny et al., 1999).

In residential indoor environments, bacterial endotoxins are believed to be another factor contributing to asthma and respiratory allergies. Endotoxins are cell wall components of Gram-negative bacteria, which are shed into the environment. According to the literature, endotoxin aerosols are ordinarily collected on filter media because they are easy to use and allow long sampling times. Dust samples are collected using a vacuum cleaner equipped with a special nozzle to collect dust on a paper filter; then gravimetric measurements and endotoxin extractions are performed. Both floor and mattress samples are common (Douwes et al., 1998). Collection with all-glass impingers has also been reported, although the literature reports that this method may underestimate endotoxin levels. More information on the characteristics and health effects related to endotoxins, as well as filter type, handling, and storage suggestions for sample collection, can be found in the American Conference of Government of Industrial Hygienists publication *Bioaerosols: Assessment and Control* (ACGIH, 1999; see Chapter 12, “Source Sampling” by Martyny et al., 1999).

3.2.1.3 Lead. Dust sampling is required by U.S. Environmental Protection Agency (EPA, 2001a) regulations (40 CFR Part 745; Lead: Identification of Dangerous Levels of Lead) for a risk assessment of a residential environment for lead based paint hazards, and protocols for sampling are well documented (40 CFR Part 745: Lead, Requirements for Lead-Based Paint Activities in Target Housing and Child Occupied Facilities; U.S. Department of Housing and Urban Development Guidelines for the Evaluation and Control of Lead-Based Paint Hazards in Housing (HUD, 1995)). For lead risk assessments, wipe sampling using moist towelettes (wet wipes) is specified by EPA regulations and HUD guidance, providing information on lead loadings per unit area, but not on lead concentrations per unit dust. Protocols specify recommendations for number, location, compositing, and analysis of dust wipe samples.

3.2.1.4 Pesticides. Pesticides may be found in airborne vapor form or adsorbed to particulates such as household dust on floors and other surfaces. Pesticides that have been measured in residential environments include chlordane, heptachlor, aldrin, dieldrin, diazinon, naphthalene, dichlorobenzene, pentachlorophenol, chlorpyrifos, malathion, and carbaryl (NAS, 2000).

Although environmental sampling is generally not a cost-effective method for assessing pesticide exposure from a housing/public health perspective, sampling to assess pesticide exposure for research purposes can be accomplished in one of several different ways. First, microenvironmental sampling for pesticide residues in air and settled dust, and on surfaces, can be combined with child activity profiles, such as respiration rates and time spent indoors, to estimate the exposure via a specific exposure pathway (Zartarian et al., 2000). Alternatively, personal samples, such as hand wipes and videotape records of child hand-to-mouth activity, can be used to estimate exposures (Reed et al., 1999). Whyatt et al. (2002) used personal air

sampling to gather data on pesticide use among pregnant women in minority communities within the New York City area; this method resulted in the detection of at least four pesticides in the personal air samples of all monitored women. Finally, measuring a biomarker of exposure, such as the excreted pesticide metabolite in urine or pesticide concentration in blood, can be used to assess the potential internal dose (Krieger et al., 2000; MacIntosh et al., 1999). Each method has strengths and limitations (Zartarian et al., 2000; Bradman and Whyatt, 2005). At this time, two of the most useful samples for assessing a child's potential residential pesticide exposure are the bulk house dust and the child's hand wipe. The former indicates "what's there" and the latter indicates "how much" the child comes in contact with when interacting with this environment.

Sampling of dust reservoirs is usually achieved using a suction/vacuum device, wipe sampling, or a dislodgeable residue sampling device. The most frequently used vacuum device for collection of floor dust for pesticide analysis is the High Volume Surface Sampler (HVS3) or HVS4 (Cascade Stack Sampling Systems, Inc.; Nishioka et al., 1996). The use of this device has been formalized as ASTM method D5438-93. Wipe sampling has typically been accomplished with Johnson and Johnson SOF-WICK gauze dressing sponges moistened with isopropanol, water, or a "sweat simulant" (Nishioka et al., 1999). Dislodgeable residue sampling can be accomplished with research devices such as the Polyurethane Foam (PUF) Roller, CDFA Roller, Dow Drag Sled, or the EL Press Sampler (Nishioka et al., 1996; Ross et al. 1991; Edwards and Liroy, 1999).

Since all of these techniques are research-type methods, they have not been subject to the same extensive intercomparison studies that were used to select and certify techniques for lead sampling. There are also drawbacks to these techniques. The HVS3 vacuum, which is based on an upright Royal vacuum cleaner, is relatively expensive (~\$3000), large, and awkward to use for routine sampling in multiple locations. The HSV4 is smaller and more portable. The dislodgeable residue samplers are research tools, and as such, are not available commercially. Several of them are somewhat cumbersome to use and are not amenable to collection of residues on surfaces other than floors.

In general, when samples are collected in homes, the primary collection sites include floor areas where children typically play (family room, bedroom, and kitchen) and wipes of surfaces that children frequently contact (tables, counters). Vacuum dust collection of floors typically covers a 1-2 m² area of these rooms; wipe sampling typically covers a smaller area, 30 cm x 30 cm (1 ft²).

3.2.2 Air Sampling

Inhalation of airborne particulates is considered the primary pathway of exposure for allergens (especially dog and cat allergens) and mold spores in homes. Potentially toxic substances such as nitrogen oxides, sulfur oxides, CO, radon, ETS, formaldehyde, and VOCs may also be present as airborne gases or particulates in indoor environments.

In general, primary types of air sampling methods include:

- Active static samplers (normally kept in a fixed location but actively drawing air into the sampler);
- Passive static samplers (normally kept in a fixed location but relying on normal airflow or particle deposition to collect contaminants on a filter or settling plate); and
- Personal breathing zone or nasal air samplers.

The static samplers are normally placed in a fixed position in a room and do not provide as accurate a measure of personal exposure as breathing zone samplers. Sampler design and flow rate have been shown to affect the quantity and size of particles sampled and thus can affect the apparent measured levels of a given airborne substance (O'Meara and Tovey, 2000). Both high-volume (60 to 1100 L/min) and lower-volume (4 to 20 L/min) filter samplers have been used, although it has been suggested that the lower volume samplers may collect a more meaningful sample in relation to exposure because they better approximate breathing volumes of humans. For example, breathing zone samplers often show much higher levels of collected allergens than static samplers, likely due to the varying levels of dust that are resuspended in the personal breathing zone as a result of human activity; however, only minor differences are observed during high levels of dust disturbance (O'Meara and Tovey, 2000).

Sampler design and flow rate have been shown to affect the quantity and size of particles sampled, and thus can affect the apparent measured levels of a given contaminant. The most commonly used methods available today for volumetric air sampling (i.e., when a known volume of air is collected) are based on one of the following principles: inertial impaction (e.g., multiple-hole impactors, slit samplers), centrifugal collection (e.g., agar-strip impactors, cyclone samplers), filtration (e.g., cassette filters attached to portable pumps), or liquid impingement (e.g., three-stage impingers) (Martyny, 1999).

Gravitation or settling techniques are also used to collect longer-term airborne allergen and mold samples by measuring the allergen or spore content of dust that settles in a petri dish or microscope slide placed in an open location for 7 to 14 days, described in units of $\text{ng}/\text{m}^3/\text{day}$ (O'Meara and Tovey, 2000); but, these techniques are non-volumetric and, due to large temporal and spatial variations, samples cannot be readily compared to one another or to volumetric samples (Martyny, 1999; O'Meara and Tovey, 2000).

3.2.2.1 Allergens. Generally, the amount of airborne allergens collected (nanograms) is far less (on the order of millionths) than the total in dust reservoirs (milligrams). The level of dust disturbance in a room, as well as the particle size, has a large effect on the amount of allergens that are airborne at any given time (O'Meara and Tovey, 2000).

Although Platts-Mills et al. (1997) reported that, in epidemiological studies through 1997, exposure to cat allergen was reported as the concentration per gram of reservoir dust, airborne cat and dog allergens have been collected and measured at relatively high levels in undisturbed conditions, in contrast to mite and cockroach allergens (O'Meara and Tovey, 2000). Because cat and dog allergens are carried on smaller airborne particulates that remain suspended in the

air for long periods of time, air sampling is often successfully used to assess these allergen levels for intervention studies.

3.2.2.2 Molds. For routine assessments in which the goal is to identify possible mold contamination problems prior to remediation, it is usually unnecessary to conduct air sampling because decisions about appropriate remediation strategies can typically be made on the basis of a visual inspection (NYC, 2000). Air monitoring may, however, be necessary in certain situations, including: 1) if an individual has been diagnosed with a disease associated with fungal exposure, 2) if it is suspected that the ventilation systems are contaminated, or 3) if the presence of mold is suspected but cannot be identified by a visual inspection or bulk sampling (NYC, 2000). In general, air sampling for molds is more technically challenging and has greater opportunity for error than source sampling (Horner, 2006). As noted previously, Chew et al. (2003) reported that concentrations of fungi in settled dust generally correlate weakly with those in indoor air. Indoor air fungi levels were strongly associated with outdoor air levels, and the investigators speculated that the two different metrics (air and dust samples) represent different types of fungal exposure, indicating that it may be necessary to collect both air and dust samples. Recent evidence suggests that very fine airborne particles (<1 micrometer aerodynamic equivalent diameter (AED)) can carry fungal fragments and/or metabolites such as allergens (Green et al., 2005; Gorny et al., 2002). Size characterization is important to detect these particulates, which could be much larger in number than spores.

Airborne mold particulates may include spores, fungal fragments, aggregates of spores or fragments, or materials contaminated with fungal product. Air sampling methods and types are discussed in the introduction of section 3.2.2. For molds, it is generally recommended in the literature that outdoor air samples are collected concurrent with indoor samples for comparison purposes, both for measurement of baseline ambient air conditions (remote from obvious mold sources), and for baseline measurement of air entering a building (samples near outdoor air intakes) (ACGIH, 1999).

When selecting a type of air sampler for fungal collection, it is recommended that consideration be given to such factors as: the compatibility of the sampler with the analysis method to be used, the type of information needed (e.g., concentration or identification of species), the concentration (e.g., very high or very low) of mold at the test site, temperature extremes, the nature of the air stream where the sample will be collected, and possible collection constraints due to the presence of occupants (ACGIH, 1999).

Comparative assessments of the performance of the different samplers (e.g., filter samplers, Andersen samplers, rotorod samplers, liquid impingers, and cyclone samplers) have been inconclusive, although certain samplers have been observed to perform better for specific purposes (e.g., the Andersen six-stage sampler for viable spore counts and the Burkard 24-hour samplers for total spore counts) (Flannigan, 1997). Many factors introduce significant variability into air sampling results and complicate interpretation. For example, air sampling collection times are important in mold investigations. Anderson samplers (multiple-hole impactors) are used for only a few minutes because of effects on the culture plate. Such short sampling times are not a practical reflection of the environmental exposure. Dillon et al. (1999)

suggested that longer sampling under usual activity levels (6-72h at 10-20L/min with collection on polycarbonate filters) gives a more representative picture of airborne fungi.

3.2.2.3 Carbon Monoxide. Combustion appliance gases, such as CO, can be assessed with differing levels of accuracy through the use of research quality and professional detection and monitoring devices. In addition, homeowners can purchase low-cost CO alarms that are designed to warn of serious, potentially lethal levels of CO in the home.

Although certain indoor CO problems can be difficult to detect due to their intermittent nature (Greiner and Schwab, 2000), a variety of field instruments are commercially available for investigation of residential CO levels, many available at a cost of less than \$300-500. The assessment of CO levels in homes by researchers and professional investigators (e.g., from the gas utility) is most often conducted using a portable commercial analyzer equipped with an active air sampler and either an electrochemical cell sensor or a nondispersive infrared (NDIR) absorption sensor. Characteristics of the various CO samplers/analyzers and factors that may affect choice of CO sensor technology for a particular use are discussed in section 3.3 on analysis of environmental samples. The EPA-designated reference methods for collecting CO measurement data for National Ambient Air Quality Standards (NAAQS) are automated methods using NDIR technology (USEPA, 2000). Other methods also commonly used to take air samples for CO measurement include canister sampling methods (for measuring low level background CO levels via gas chromatography) and passive samplers (e.g., badges) used to monitor personal exposure to CO.

In addition to CO monitoring devices used in professional monitoring and inspection, a variety of CO detectors/alarms available on the market today sample indoor air on a continual basis and thus provide a longer-term picture of home CO levels. CO alarms are intended primarily to provide early warning of potentially dangerous CO levels (generally above 70 ppm), but also to offer some protection against chronic lower level exposures. Alarms that use household current typically employ a solid-state sensor that purges itself and resamples CO on a periodic basis. Battery-powered alarms typically use a passive sensor technology that reacts to prolonged exposure to carbon monoxide gas. Several of the most common CO sensor technologies currently employed in CO alarms for residential use are discussed in section 3.3 on analysis of environmental samples.

3.2.2.4 Pesticides and Other Toxics. In indoor environments, substances such as pesticides, nitrogen oxides, sulfur oxides, CO, ETS, formaldehyde, and VOCs are found as airborne gases or particulates. Assessment of these hazardous substances is primarily achieved via passive or active area air sampling. Unvented cooking and heating appliances that burn gas or kerosene and fireplaces are important sources of numerous pollutants, including nitrogen oxides, CO, sulfur oxides, formaldehyde, VOCs, and particulates. Formaldehyde is also emitted by some building materials (especially new materials) and furniture. Other indoor sources of VOCs include cigarette smoking, solvents, particleboard, chlorinated water, dry-cleaned materials, caulks, adhesives, mothballs, paints and stains, room deodorizer, and vinyl flooring. Because pesticides are found in both vapor form and adsorbed to particulates, both air and dust sampling are used to assess pesticides.

3.3 Analysis of Environmental Samples

3.3.1 Allergens

3.3.1.1 Immunoassays and Particle Immunostaining. For allergen analysis, collected dust samples are typically sieved to separate out the fine dust fraction (i.e., using a 60-mesh metal sieve that allows particles smaller than 250 µm in diameter to pass through), which is then extracted with a buffer solution, serially diluted, and then applied to the appropriate quantitation test. To measure allergen levels, enzyme-linked immunosorbent assays (ELISAs, a specific type of immunoassay) have been developed for many allergens. Immunoassays are a laboratory technique that makes use of the specific binding between the antigen associated with an allergen and its homologous antibody in order to identify and quantify a substance in a sample. They generally provide very accurate quantitation (Chapman et al., 2000). However, although immunoassays for numerous allergens have been developed, only relatively few are readily available from commercial laboratories. Those that are typically available include immunoassays for dust mite (Der p 1 and 2, Der f 1 and 2, and Blo t 5), cat (Fel d 1), dog (Can f 1), mouse (Mus m 1), rat urine (Rat n 1), and cockroach (Bla g 1 and 2) allergens (e.g., see Indoor Biotechnologies, Inc. at <http://www/inbio.com/index.html>). Immunoassays have also been developed for several important indoor mold allergens, including those from *Aspergillus fumigatus*, *Alternaria alternata*, and *Cladosporium herbarum* (Bush and Portnoy, 2001). However, immunoassay technology for molds is not as highly developed or well-standardized as that for house dust mite, animal, or cockroach allergens (Bush and Portnoy, 2001). Only assays for *Alternaria* (Alt a 1) and *Aspergillus* (Asp f 1) are currently widely available (Vailes et al., 2001).

At present, many different immunoassays are being used to measure the same allergens, but comparisons of allergen levels in different studies can be made using standard reference preparations. To date, international reference preparations for allergens have been developed by the World Health Organization (WHO) only for one species of mite (*D. pteronyssinus*) and for dog allergen (Chapman et al., 2000). However, other standards for mite, cat, dog, and cockroach have been developed by numerous research groups and companies and are widely available in the U.S. for 'in-house' or commercial use, although their stability and accuracy has not yet been established (Platts-Mills et al., 1997). Nevertheless, a recent review of allergen detection and avoidance measures recommends the use of home collection kits as an alternative to professional sampling during home inspections for measuring allergen levels in settled dust (Eggleston, 2003).

Particle immunostaining is a relatively new technique that involves a protein-binding membrane, immunostaining of bound allergens, and examination of stained samples under a microscope where the density of staining is determined using image analysis (O'Meara and Tovey, 2000). This technique has been used in research settings to measure airborne mite (Der p 1 and Der p 2), cockroach (Bla g 1), cat (Fel d 1), dog (Can f 1) and *Alternaria* allergens in undisturbed indoor environments (Poulos et al., 1998; De Lucca et al., 1998; Tovey et al.,

1998; and O'Meara et al., 1998, as cited in O'Meara and Tovey, 2000). It is extremely sensitive (on the order of sub picograms of allergen) and appears to have high repeatability in combination with nasal air samples (O'Meara and Tovey, 2000).

3.3.1.2 New Techniques for Home Testing of Allergens. Immunoassays are generally time-consuming and require specialized laboratories. Recently however, as the importance of indoor allergen avoidance and the need for simple, rapid, dust sampling and allergen testing has become apparent, several office or home-based testing technologies have been developed. A few simple test kits that use monoclonal antibody (MAb)-based technology (the technology used in home pregnancy tests) are currently available. These technologies use antigen-specific antibodies that are attached to membranes (as dipsticks or cassettes) to bind proteins present in a sample (in this case, allergens present in an extracted and diluted sample). In the final step of the test, a second allergen-specific antibody that has an additional molecule linked to it, such as an enzyme that changes the color, is then added. If a specific allergen is present, the intensity of the color that is produced is in proportion to the allergen concentration. In the absence of the allergen, the second purified antibody will not be bound, and no change in sample color will occur. For allergen screening of indoor samples, these types of tests usually only provide a result above or below a threshold value (O'Meara and Tovey, 2000). Some of these tests can detect multiple allergens using one dust sample, such as a commercial method called DUSTSCREEN® (CMG-HESKA, Fribourg, Switzerland) which can detect *D. pteronyssinus* and *D. farinae* mite allergen, *Felis domesticus* (cat) allergen, and *Blattella germanica* (cockroach) allergen (Chapman et al., 2000; DeWeck et al., 1998 as cited in Chapman et al., 2000).

Two types of quick tests have also been developed specifically for dust mites, including the ACLOTEST® and the gold-based lateral flow quick test (Chapman et al., 2000). The gold-based lateral flow test (Rapid Test for Mite Allergens (RAPID®)) is sensitive to a detection limit of approximately 100 pg, detects both *D. pteronyssinus* and *D. farinae*, and produces results within 10 minutes (INDOOR Biotechnologies, Ltd. at http://www.inbio.com/Rapid_Test_Kit.html) (Chapman et al., 2000; Tsay et al., 1999). The ACLOTEST® (Lofarma, Milan, Italy) detects *D. pteronyssinus* and *D. farinae* mite allergens (including Der p1 and Der f1) and is sensitive to 0.5 µg/g dust (Allergy Buyers Club, <http://shop.store.yahoo.com/purenatural/00-dmtk.html>) (Mistrello et al., 1998 as cited in Chapman et al., 2000).

A home dust collection device called the MITEST® collector has also been developed and consists of a collector that fits on the end of a tube wand vacuum (INDOOR Biotechnologies, Ltd. at http://www.inbio.com/Mitest_Dust_Collector.html). After vacuuming for 2 minutes, the collector is capped, shaken with an extraction solution for 5 minutes, and then applied to the allergen test. Using this collector together with the RAPID® gold-based lateral flow test, a dust sample can be collected, extracted, and tested within 15 to 20 minutes (Chapman et al., 2000).

3.3.2 Mold

Current methods available to analyze environmental samples from the home for mold hazards include:

- Counting colonies cultured for certain species.
- Identifying and/or counting spores.
- Chemical analysis of fungal components and biochemical/immunochemical markers to quantify total fungal loads (biomass).
- Immunoassays (ELISAs) to measure fungal-specific antigen levels.
- Polymerase chain reaction (PCR) based technologies (i.e., genetic probes) to identify fungal species.

No single method provides a complete assessment of the exposure hazard associated with an environmental sample. The quality of environmental microbiology laboratories performing analyses on samples for molds and other microbiological agents is monitored under an external peer review program sponsored by the American Industrial Hygiene Association (AIHA). This program, which includes the Environmental Microbiology Proficiency Analytical Testing (EMPAT) Program and the Environmental Microbiology Laboratory Accreditation Program (EMLAP), is specifically for labs identifying microorganisms commonly detected in air, fluids, and bulk samples during indoor air quality studies. EMPAT is a performance evaluation program that uses proficiency testing to score participating laboratories. Proficiency in EMPAT is mandatory for labs seeking EMLAP accreditation and in the absence of standard methods, using laboratories with an accreditation, such as from the EMLAP, is desirable (Horner, 2003). When a laboratory is accredited by AIHA, the laboratory and its clients have the assurance that the laboratory has met defined standards for performance based on examination of a variety of criteria. Proficiency in EMPAT is mandatory for labs seeking EMLAP accreditation. Additional information on the EMPAT and EMLAP programs is available online at <http://www.aiha.org/SplashPages/html/topic-mold.htm>.

3.3.2.1 Culture Methods and Spore Examination. The growth of fungal colonies on specially prepared nutrient media (culture) from spores contained in air or dust samples is a common method used to assess mold populations. However, because allergenic spores may not be viable (i.e., culturable), the culture method may underestimate true allergenic potential. Also, in cultures containing multiple species (as is often the case) some species may not compete well and may not grow sufficiently for accurate enumeration or even identification. Following culture, identification of fungal species can often be accomplished with a dissecting or light microscope via examination of colony morphology or spore bearing structures. Culture results can also be reported in terms of colony forming units (CFU) per m³, g, or cm². The type of isolation media used to culture the fungal spores can introduce substantial variability into the types and relative magnitudes of mold species that are cultured (Burge and Otten, 1999; Flannigan, 1997). Bias in culture measurements may be introduced because a highly nutritionally rich substrate favors the growth of fast-growing species, or because one species present in the sample may not compete well with another on the culture plate (Flannigan, 1997). For example, some genera such as *Penicillium* grow well and quickly on most media

and thus may be over-represented in a culture sample, while others such as *Stachybotrys* grow slowly or not at all on commonly used substrates (Bush and Portnoy, 2001).

Non-culture methods can also be used to estimate total fungal allergen loads (biomass), although, generally, these methods do not allow for identification of species. Many types of fungi are identifiable to the genus or species level, depending on the type of fungi sampled, via microscopic examination of spores in collected air and source samples (Burge and Otten, 1999; Pinchin Environmental, 2002). Spore counts can also be reported, typically in units of spores per m³, g, or cm². This method is relatively inexpensive, but time-consuming, and can give a general indication of atypical indoor mold growth.

3.3.2.2 Chemical Analyses for Fungal Components. Methods using chemical analysis can be used to quantify total fungal loads (biomass), although these methods generally do not allow for identification of species. These methods can be based on chemical components (biomarkers) common to a particular group of organisms, such as ergosterol in the membranes of fungal hyphae and spores (Flannigan, 1997). These markers can indicate the relative extent and presence of fungal growth but do not measure fungal allergen exposure. Furthermore, their use in quantifying fungal exposure and its relationship to human allergic disease is highly investigational (Bush and Portnoy, 2001). Results of dust analysis are typically expressed as concentration in units of weight of analyte per weight of settled dust. Results of air sample analysis are usually expressed volumetrically.

Mycotoxins. Methods currently available for detecting mycotoxins in environmental samples were designed for testing agricultural products and generally do not translate well to residential testing requirements (e.g., air samples with very low mycotoxin concentrations) (Burge and Ammann, 1999). Thin layer chromatography has been used to measure mycotoxins in some studies, although the usefulness of this technique is limited due to lack of sensitivity and susceptibility to interference (Burge and Ammann, 1999). High performance liquid chromatography (HPLC) and gas chromatography with mass spectrometric detection (GC-MS) have also been used for mycotoxin quantitation, although these techniques are also limited due to specialized laboratory requirements and associated expense (Burge and Ammann, 1999). Various researchers have measured cell toxicity of particulate air samples and inferred the presence of mycotoxins. For example, Vesper et al. (2000) used a protein synthesis inhibition assay to evaluate the toxicity of air particulate samples during a *Stachybotrys chartarum* remediation study. Protein synthesis inhibition is an activity characteristic of trichothecene mycotoxins typically produced by *Stachybotrys*. Field sample extracts were assayed for trichothecene toxicity by comparison to a known sample, with the results expressed as toxin equivalents per cubic meter of air. Mycotoxin analysis can be used to detect the presence of certain fungi in the environment; but, more commonly, mycotoxin levels are only measured after the fungal species has been identified (Bush and Portnoy, 2001).

Other Chemical Components of Fungi. Ergosterol, which is a component of fungal cell membranes, has been used as an index of fungal mass in house dust and air samples and can be analyzed using gas chromatography with mass spectrometric detection (Flannigan,

1997; Dillon et al., 1999). Ergosterol is not present in vascular plants, and therefore, in most indoor environments can be used as a specific measure of fungal mass (Dillon et al., 1999). Ergosterol measurement has been applied in assessments of house dust and air (Dillon et al., 1999), although, as with mycotoxin analysis, this highly specialized technique may have resource limitations for home assessments.

There are about 15 volatile organic compounds (VOCs) produced by fungi that may also be used as markers of fungal growth, although some are also emitted by bacteria (Dillon et al., 1999). VOCs can be collected on solid sorbents, extracted, and quantified using gas chromatography with mass spectrometric detection. Measurement of fungal VOCs may be particularly useful in some home assessments for detection of hidden mold growth because the compounds can permeate porous walls in buildings (Dillon et al., 1999). However, the uncertainties currently associated with accuracy of these methods preclude using this approach for routine investigations. For example, significant questions remain regarding reliable “signature” VOCs for a particular fungus and how to deal with the variability in VOC produced under different conditions (Ammann, 1999).

3.3.2.3 Immunoassays for Fungal Allergens and Other Components. To measure mold allergen levels in collected dust and air samples, enzyme-linked immunosorbent assays (ELISAs, a specific type of immunoassay) have been developed for some indoor mold allergens and some mold components such as (1→3) β -D-glucan and extracellular polysaccharides. However, this technology for fungal allergen quantitation is not as highly developed or well-standardized as that for house dust mite, cat, or cockroach allergens (Bush and Portnoy, 2001). Currently, monoclonal antibody ELISAs for *Alternaria* (Alt a 1) and *Aspergillus* (Asp f 1) are available from commercial laboratories (e.g., see Indoor Biotechnologies website at <http://www.inbio.com/services.html>) (Vailes et al., 2001).

β (1→3)-D-glucan, a component of fungal cell walls, can be analyzed using a modification of the *Limulus amoebocyte* lysate (LAL) technique or enzyme inhibition assay (EIA) and has also been used to measure total fungal biomass in house dust and air (Dillon et al., 1999; Flannigan, 1997). However, β (1→3)-D-glucan is not specific to fungal cell walls and may originate from plants and some bacteria (Douwes et al., 1998). In addition, a standardized protocol for the storage, extraction, and analysis of environmental samples for β -glucan is not well developed (Dillon et al., 1999). Furthermore, only a few laboratories test environmental samples for β -glucan (Halsey, personal communication, 2004).

Mold extracellular polysaccharides (EPS) have potential usefulness as fungal measures, as they are produced in mycelial cell walls under almost all growth conditions (Dillon et al., 1999). Douwes et al. (1999) examined the relationship between measured EPS from *Aspergillus* and *Penicillium* species (EPS-*Asp/Pen*) and culturable fungi, reported home dampness, and respiratory symptoms. EPS-*Asp/Pen* levels were significantly correlated with total culturable fungi, and levels in living room floor dust were positively associated with home dampness and respiratory symptoms. EPS can be measured using a specific enzyme inhibition assay (EIA),

although the determination of EPS has not yet been routinely applied in indoor studies (Dillon et al., 1999).

3.3.2.4 Genetic Probes for Molds. Quantitative polymerase chain reaction (QPCR) based technologies (i.e., genetic probes), unlike other non-culture methods, can be used to identify certain biological particles such as fungi to the species level (Flannigan, 1997). The technology is based on targeting short, species-specific sequences of DNA. EPA's Office of Research and Development, National Exposure Research Laboratory, has recently refined a DNA-based system that allows rapid identification and quantification of molds in a matter of hours. The analytical methods are published at the website: <http://www.epa.gov/nerlcwww/moldtech/htm>.

Beneficial attributes of QPCR are: (1) it is species specific, which may allow assessment for certain mold species known to be associated with health effects or environmental conditions; (2) unlike live culture analysis, it reports non-viable as well as viable molds, which is important because non-viable molds are potentially allergenic; (3) it results in fewer "non-detects" than live culture analysis; (4) it is apparently more reliable than live culture analysis because not all species may grow on the media used and because fast-growing species may overtake the slow-growing species; (5) it finds higher concentrations than culture analysis, sometimes by orders of magnitude; and (6) it is quicker and easier (Vesper et al., 2005; Vesper et al., 2004; Meklin et al., 2004). In recent studies, the cited investigators found that QPCR results did not correlate with culture-analysis results. Also, results of QPCR-analyzed settled-dust samples did not correlate with QPCR-analyzed short-term air samples (five minutes or less); similar results have been reported based on viable count methods. Current disadvantages of QPCR include the facts that DNA probes have been developed for only 130 fungal species, and the relatively high cost.

3.3.3 Endotoxins

Endotoxin analysis in a laboratory setting uses a kinetic limulus assay (specifically, a Limulus amebocyte lysate assay) to measure endotoxin content. Endotoxin concentrations are expressed as units per gram of house dust and per square meter of surface area (Braun-Fahrlander, 2002). Douwes et al. (1998) found that the highest endotoxin concentrations were detected on living room floors, while the lowest concentrations were found for mattresses both when concentrations were expressed per gram of dust and per square meter. More information on limulus amebocyte lysate (LAL) assays and sample analysis (quantitative LAL assays, parallel-line LAL assays, interferences with LAL assays, and variability in LAL reagents) can be found in the American Conference of Government of Industrial Hygienists publication *Bioaerosols: Assessment and Control* (ACGIH, 1999; see Chapter 12, "Source Sampling" by Martyny et al., 1999).

3.3.4 Carbon Monoxide

NDIR absorption sensor technologies, which are based on the specific absorption of infrared radiation by the CO molecule, are generally accepted as the most reliable, continuous methods for measurement of CO in ambient air and are extremely sensitive over wide concentration

ranges. Portable analyzers with the capability to measure extremely low-levels of ambient CO using NDIR technology are available for home assessments, although they are expensive (e.g., up to tens of thousands of dollars) and typically used only in research settings where the extra sensitivity is needed. The most sensitive, commercially available analyzers using NDIR technology are able to detect minimum CO concentrations of about 0.02 ppm (USEPA, 2000). The EPA-designated reference methods for collecting CO measurement data for NAAQS are automated methods using NDIR technology (USEPA, 2000). Electrochemical sensors, which are based on the measurement of electrical currents generated as a result of chemical reactions that occur in the presence of CO, are generally less sensitive than NDIR sensors and more sensitive to interference from water vapor and other gases. However, although the electrochemical technology, which is also used in certain types of home CO alarms, is less sensitive and more susceptible to interferences than NDIR technology, it is less expensive (e.g., typically a few hundred dollars) and sufficiently sensitive (some down to 1ppm) for the identification of CO poisoning hazards. For routine CO screening, or in situations where the goal is to identify higher concentrations of CO that represent a health risk, palm-held electrochemical sampler/analyzers are most commonly used. Upper-end (e.g., up to a few thousand dollars) electrochemical sensor analyzers are available that, with frequent recalibration, can exhibit sensitivities comparable to NDIR. The normal performance range expected for automated CO analyzers is 0 to 1,000 ppm, with some instruments available that offer higher or lower ranges for specific uses (USEPA, 2000). For example, a CO analyzer with a range up to about 1,000 ppm might be needed to monitor CO levels in a parking garage. Regardless of which sensor technology is used, it is recommended that the results be evaluated by frequent calibration with CO samples of a known concentration (USEPA, 2000). Other methods also commonly used to assess CO levels include gas chromatography/canister sampling methods for measuring low level background CO levels, and passive samplers (e.g., badges and spot detectors) used to monitor personal exposure to CO.

In comparison to monitoring devices used in professional inspections, sensors used in home CO alarms are primarily intended for the purpose of providing early warning of potentially dangerous CO levels (generally above 70 ppm) and therefore do not need a high level of sensitivity or a large detection range. Home CO alarms typically cost about \$20 to \$60. The most common CO sensor technologies currently employed in CO alarms for residential use include: colorimetric reagent (i.e., biometric or biomimetic) sensors, in which a change in the color of a gel-coated disc sounds an alarm; metal oxide semiconductor (MOS) sensors, which determine CO levels by reaction with a heated metal (tin oxide); and electrochemical cell sensors, in which a chemical reaction with CO creates an electrical current, setting off an alarm. The colorimetric alarms tend to have the lowest cost, and the MOS alarms have the longest life (Kwor, 2000). The review by Kwor (2000) concludes that the electrochemical alarms “exhibit the best overall combination of cost and performance” (Kwor, 2000). Although there are no mandatory national standards in place for CO alarms, the quality of CO alarms available for purchase today is greatly influenced by self-imposed industry performance criteria, which provide recommended performance requirements for alarms, as well as general criteria for their construction and testing. The U.S. CPSC recommends that consumers purchase home alarms that meet specifications established by Underwriters Laboratories (UL) 2034 standard for CO detectors/alarms, “Single and Multiple Station Carbon Monoxide Detectors” (UL, 2002) or the

Canadian Standards Association CAN/CSA 6.19-01, and the previous International Approval Services IAS 6-96. All three organizations are well respected standards developers and their standards are equally acceptable to the CPSC staff.

3.3.5 Pesticides

Chemical analyses for pesticides in environmental media and biomarker samples frequently involve extraction, cleanup and detection using gas chromatography/mass spectrometry (GC/MS). Other detection methods include gas chromatography electron capture detection (GC/ECD), gas chromatography with nitrogen-phosphorus detection (GC/NPD), and liquid chromatography mass spectrometry (LC/MS). While the overall process of pesticide analyses is relatively labor-intensive, the protocols and methods can be adapted so that multiple residues, even as many as 25-30 analytes from the same chemical class of pesticides, can be analyzed in the same sample extract (Chuang et al., 1999). However, in general, pesticide analyses are costly; therefore, pesticides are often only routinely assessed in research studies.

3.4 Interpretation of Results

The challenge in interpreting results from either visual assessment, occupant surveys or from environmental sampling is twofold: first, determining the degree to which the results indicate potential for human exposure and health effects, and second, determining the relative severity of different individual hazards. In general, there is significant variability in sample results dependent on the time and location of sampling and significant uncertainty concerning the relationship between environmental samples and exposure. Experience with lead-based paint risk assessments illustrates areas that must be addressed. These include: characterizing the various pathways of exposure and the relationship of environmental samples and occupant behavior to those pathways; characterizing factors that affect the representativeness and variability of environmental samples or other assessment information; and determining health-based standards against which the assessment results can be compared. An extensive discussion of the factors associated with exposure and risk for the multiple health endpoints associated with residential hazards is beyond the scope of this paper. However, the following is a discussion of some representative issues associated with interpretation of a healthy homes risk assessment. Other important issues related to the interpretation of environmental samples remain, and many of these are topics for future research as discussed below in Section 4.

3.4.1 Allergens

The primary route of exposure to allergens is presumed to be inhalation of airborne particles, and thus reservoir levels are not good markers for short-term exposures. For example, due to activity and resulting dust disturbance in a home, studies have found large variations in the amount of a specific allergen that is airborne at a given time, often with a 50-fold difference in the concentrations of airborne allergens detected in homes within one experiment (O'Meara and Tovey, 2000). Another limitation of assessing exposure via the concentration of allergen per gram of settled dust is that it does a poor job of characterizing the total allergen burden in a house, due to differences in amounts of total dust (NAS, 2000). The correlation between

airborne and dust reservoir allergen levels has not been well studied, but some data suggest that reservoir dust concentrations are poor predictors of airborne levels (O'Meara and Tovey, 2000). O'Meara and Tovey (2000) suggest that this may be, in part, due to the fact that reservoir levels are usually expressed as concentrations (μg allergen per gram of dust). Expressing reservoir levels as surface loadings (μg per m^2) may be a more appropriate measure of reservoir allergen for purposes of predicting airborne levels (Takaro et al., 2004). In general, however, the measurement of allergen concentrations in dust is currently more feasible and consistent than air sampling, and it is therefore usually employed.

Regarding pet allergens, Platts-Mills et al. (1997) suggested that cat allergen concentrations in reservoir dust might not adequately characterize inhalation exposure. However, for the purposes of low-cost health assessment in a residential setting, environmental sampling would not be necessary where the presence of a pet, and thus pet allergen, is known or can be imputed.

There is also considerable variability associated with the determination of allergen-specific concentrations in dust samples using ELISA. HUD initiated a study in which commercial, academic, and municipal laboratories were provided with dust samples from the same batches of reference dust to analyze for up to six allergens (Pate et al., 2005). Coefficients of variation on the estimated geometric mean allergen concentrations ranged from 61% - 93%, and in most cases between-laboratory variability in analytical results was significantly greater than within-laboratory variability. The results indicated that analytical results could generally be used to determine if allergen-specific concentrations exceeded thresholds of interest with reasonable certainty; however, they also supported the importance of improving the standardization of laboratory procedures for processing and analyzing samples for allergens using ELISA methods.

3.4.2 Mold

Methods for assessing human exposure to fungal allergens and mycotoxins are relatively poorly developed (NAS, 2000), and interpretation of results is difficult. This is due, in part, to the fact that fungal allergens and toxins vary widely across mold species and that traditional methods of mold population assessment (e.g., spore counts) do not have consistent relationships with levels of mold allergens or toxins. Furthermore, because viable mold measures do not include particles that are not culturable (non-viable spores or non-reproducing vegetative fragments) but that may have toxic or allergenic properties, investigations of mold-affected houses that focus only on assessing the number of culturable organisms may underestimate actual allergenic or toxic potential (Flannigan and Miller, 1994; Flannigan, 1997). Conversely, total measures of a fungal component (e.g., ergosterol or glucan) in a sample do not allow for identification of mold species or provide information about the biologically active portion of the sample. Therefore, neither measure provides a complete assessment of the potential allergen or mycotoxin exposure hazard associated with an environmental sample. The accuracy of substituting measures of exposure to fungi for exposure to fungal allergens or toxins has not been determined (ACGIH, 1999), and direct measurement of allergens and toxins is limited by

the current development and standardization of immunoassays for specific allergens and reliable, affordable techniques for mycotoxin analysis.

Further complicating the exposure assessment is variability associated with the collection of samples. The accuracy of quantifying air samples is complicated by large variations in airborne concentrations from room to room and temporally over relatively short periods of time, as well as outdoor concentrations with season (O'Meara and Tovey, 2000; Flannigan, 1997; Flannigan and Miller, 1994). Dust sampling for molds is sometimes used to circumvent this temporal variability, although dust samples sometimes show differences in the relative abundance and types of mold in comparison to air samples (Flannigan, 1997; Dillon et al., 1999). The release of molds from carpets and walls or other surfaces has also been cited as an important factor in introducing variability into the magnitude and nature of indoor air spora collected (Flannigan, 1997). In addition, due to the ubiquitous presence of mold spores in the outdoor environment (often in concentrations far higher than indoors), it can be difficult to establish the presence of indoor mold growth using air sampling. Moisture availability, in addition to affecting the extent of mold colonization, also affects the types of mold present. Some of the most abundant fungi genera found in homes without severe water damage include: *Alternaria*, *Cladosporium*, *Penicillium*, yeasts, and *Aspergillus* (Burge and Otten, 1999; American Academy of Pediatrics, 1998; Bush and Portnoy, 2001; Gravesen et al., 1999). Most of these molds do not typically produce mycotoxins (Etzel, 2000) but may be important as sources of mold allergens. In contrast, under certain very damp conditions (i.e., in the presence of water-soaked cellulosic materials), toxin producing *Stachybotrys chartarum* may be prominent (Flannigan, 1997). In general, whether or not a potentially toxigenic fungus produces toxins is dependent on environmental conditions and nutrient source (Burge and Ammann, 1999). At this time, there remain many uncertainties regarding interpretation of mold measurements from air sampling.

Professional inspectors frequently compare the types and levels of fungal organisms detected in various environments, e.g., outdoors vs. indoors, as a way of interpreting microbiological results. The qualitative diversity of airborne fungi outdoors should be similar to that measured indoors in the absence of mold contamination. Conversely, if one or more types of fungi dominates the indoor environment but is not detected outdoors, the sampled building may have a moisture problem and fungal contamination. However, that may not always be true. Spores of some outdoor fungi may infiltrate a house and persist under normal conditions long after outdoor sources are no longer present (Horner, 2006). In addition, levels of spore counts can vary by region and season (Gots et al., 2003; Ren et al., 1999).

Another common indicator of indoor moisture problems is the consistent presence of fungi such as *Stachybotrys chartarum*, *Aspergillus versicolor*, or various *Penicillium* species at levels well above background concentrations (AIHA, 2003).

Using mold specific quantitative polymerase chain reaction (MSQPCR), Vesper et al. (2004) and Meklin et al. (2004) found that certain molds, which they labeled Group I molds, are found in higher concentrations in water-damaged homes than in other homes, while other molds (labeled Group II molds) are found in all homes. Group I molds included, but were not limited to: *Apergillus restrictus*, *Penicillium brevicompactum*, *Aspergillus niger*, *Paecilomyces variotii*,

Aspergillus ochraceus, and *Trichoderma viride*. One way this information may be useful is in identifying homes that have suffered water damage but do not display easily identifiable signs of it. Another may be in narrowing the list of molds for which PCR analysis is necessary. Also, the investigators compared PCR-analyzed dust sample results from water-damaged homes of asthmatic children with those from control-group homes and found (1) that only Group I molds had higher concentrations in the water-damaged, asthmatic-occupied homes compared to the control homes, and (2) that certain Group I mold species had significantly higher concentrations (Vesper et al., 2005). The authors concluded that “if Group I molds are discovered, water-damaged remediation and mold removal might be considered as part of the total prevention plan in an asthmatic child’s home.”

3.4.3 Pesticides

Sampling for pesticide residues in settled dust and on surfaces, as well as in air, can be combined with child activity profiles, such as respiration rates and time spent indoors, to estimate the exposure via a specific exposure pathway (Zartarian et al., 2000). Personal samples, such as hand wipes and videotape records of child hand-to-mouth activity, can be used to estimate exposures to pesticides (Reed et al., 1999). As mentioned previously in Section 3.2.1.4, each method, at this stage of development, has strengths and limitations (Zartarian et al., 2000). For example, children who display frequent hand-to-mouth behavior may have low hand wipe pesticide residues but high hand-to-mouth pesticide exposures. Despite potential limitations, at this time, two of the most useful samples for assessing a child’s potential residential pesticide exposure are the bulk house dust and the child’s hand wipe.

3.4.4 Carbon Monoxide

Carbon monoxide poisoning may occur as a result of both short-term (minutes to hours) exposures to high concentrations of CO (acute exposure) and longer-term exposures (days to months) to relatively low concentrations of CO (chronic exposure). Thus, carbon monoxide hazard levels are typically expressed as airborne concentrations in parts per million (ppm) and duration of exposure.

Average indoor CO levels typically vary from 0.5 to 5 ppm, although they may be much higher under certain conditions (Wilson et al., 1993). Studies conducted by Wilson and Colome investigated a random sample of residences in California for the purpose of estimating a statewide distribution of indoor CO concentrations. Based on this analysis, the estimated 95th percentile of 48-hour average CO concentrations in California residences was 5.8 ppm. The estimated 95th percentile value for the maximum 10-minute exposure was 18.6 ppm (Wilson et al., 1993). These values provide some context for determining when an indoor CO concentration is abnormally high in comparison to average levels. Generally, all-electric homes have lower CO readings than homes that have combustion appliances, although other CO sources can present a CO hazard in these homes. Higher net indoor CO levels (indoor minus outdoor CO concentrations) in the Wilson and Colome studies were traced to space heating with gas ranges and unvented gas-fired wall furnaces, use of gas ranges with continuous gas pilot lights, homes with small volumes (e.g., mobile homes), and cigarette smoke. However,

several other factors may also have contributed to the higher CO levels observed in these studies: malfunctioning gas furnaces, automobile exhausts leaking into homes from attached garages and carports, improper use of gas appliances (e.g., gas fireplaces), and improper installation of gas appliances (e.g., forced air unit ducts) (Wilson et al., 1993; Colome et al., 1994). Transiently elevated CO levels in homes caused by intermittent sources, such as appliances used only occasionally or downdrafting, may be difficult to detect. For example, although average long-term concentrations of CO from gas cooking stoves are not expected to be significant due to their intermittent use, short-term peak CO concentrations of 1.8 to 120 ppm have been associated with these stoves (USEPA, 2000). In addition, even when elevated CO level are detected (e.g., by a CO alarm sounding), the source, or sources, may be difficult to isolate.

3.4.5 Quantitative Standards or Guidelines for Comparison

Finally, there is the issue of comparison of results to standards that indicate potential hazard. As noted by Krieger and Higgins (2002), national unified guidelines or standards for many of the factors we now know to influence healthful housing are urgently needed. The major limitations with existing quantitative guidelines for allergens, fungi, and indoor air contaminants are the lack human dose/response data, uncertainty regarding the relative importance of different risk factors and exposure pathways and their interactions, and the lack of standardized protocols for data collection, analysis, and interpretation. In particular, the development of standards or guidelines protective of children is also poses a large challenge in public health. Because of the unique patterns of exposure and special vulnerabilities of children, home risk assessment approaches that move beyond consideration of average levels of exposure for adults are also needed (Landrigan et al., 2004).

3.4.5.1 Allergen Guidelines

Table 5. presents threshold levels that have been proposed or suggested for common indoor allergens, against which allergen levels in the home may be compared to determine the level of potential hazard.

Table 5. Current Threshold Levels for Assessing Common Residential Allergens

Allergen	Threshold Level		Typical Sample Characteristics
	Allergic Sensitization	Asthma Symptoms	
Dust mite allergen (Der f 1 + Der p 1)	2 µg/g ^a	10 µg/g ^a	Collection: Dust, by vacuuming (bed and bedroom) Analysis: Assay group 1 allergens (µg/g) or dust mite count
Cockroach allergen (Bla g 1)	2 Units/g ^b	8 Units/g ^b	Collection: Dust, by vacuuming (bedroom, kitchen, bathroom); trapping Analysis: Assay of allergens (Units/g) or cockroach identification and counts
Cat (Fel d 1)	1 µg/g ^c	8.0 µg/g ^c	Collection: Dust, by vacuuming (living room floor and furniture); air sampling Analysis: Assay of allergens (µg/g)
Dog (Can f 1)	2 µg/g ^c	10 µg/g ^c	Collection: Dust, by vacuuming (living room floor and furniture); air sampling Analysis: Assay of allergens (µg/g)
Mouse (Mus m 1)	1.6 µg/g ^c	--	Collection: Dust, by vacuuming (whole house); air sampling Analysis: Assay of allergens (µg/g)
Fungal allergen	No allergen specific thresholds ^d		Collection: Air sampling; surface sampling Analysis: Spore counts, culturable fungi, total biomass/biomarker

^a Platts-Mills et al., 1995

^b Eggleston and Arruda, 2001

^c Cat and dog threshold levels used by Ingram et al. (1995) and Custovic et al. (1998b). Mouse levels based on Phipatanakul et al. (2000b).

^d Bush and Portnoy (2001) suggest that indoor spore counts equal to or greater than 1000/m³ and colony counts on the order of 1000 to 10,000 CFU per m³ likely represent indoor fungal contamination. Portnoy et al. (2005) concluded that “total airborne spore counts attributable to indoor sources greater than 1,000 spores/m³ indicate a concern and those greater than 10,000 spores/m³ indicate a definite problem.” Other suggested guidelines for the upper limit for airborne fungi in non-contaminated indoor environments reported in the literature range from less than 100 colony forming units (CFU) per m³ to greater than 1000 CFU per m³ (Rao et al., 1996). Established threshold levels for mold species or genera do not exist at this time (Jacob et al., 2002).

Table 5 provides estimated threshold levels (as mass concentration in a dust sample) for common residential allergens for both allergic sensitization and asthma symptom exacerbation, i.e., the level representing a risk of sensitization to the allergen and the level at which most allergic patients will experience symptoms. Except for dust mites, these threshold levels are not well established.

3.4.5.2 Carbon Monoxide Standards

Selected standards for CO are presented in Table 6.

Table 6. Selected Standards and Guidelines¹ for Carbon Monoxide

Standard	Agency & Purpose
9 ppm	▪ EPA's National Ambient (outdoor) Air Quality Standard – 8-hr average
	▪ World Health Organization's outdoor air limit – 8-hr average
≤ 11 ppm	▪ Health Canada's Exposure Guideline for Residential Indoor Air – acceptable short-term exposure range, 8-hr average
≤ 25 ppm	▪ Health Canada's Exposure Guideline for Residential Indoor Air – acceptable short-term exposure range, 1-hr average
30 ppm	▪ Lowest CO level that UL and CSA allow home CO alarms to display, must not alarm in less than 30 days
35 ppm	▪ EPA's National Ambient (outdoor) Air Quality Standard – 1-hr average
50 ppm	▪ OSHA's 8-hr time-weighted average exposure for workers
	▪ EPA's Significant Harm Level for ambient CO per 8 hr time-weighted average
70 ppm	▪ UL and CSA false alarm resistance point at 60 minutes (1 hr) of exposure
	▪ Level at or above which UL and CSA home CO alarms must go off when exposed for 60-240 minutes (1-4 hrs)
75 ppm	▪ EPA's Significant Harm Level for ambient CO per 4 hr time-weighted average
125 ppm	▪ EPA's Significant Harm Level for ambient CO per 1 hr
150 ppm	▪ Level at or above which UL approved CO alarms must go off within 10-50 minutes of exposure
200 ppm	▪ NIOSH ceiling concentration for workers at which immediate evacuation is recommended
	▪ (Air free) Level of CO allowed inside water heater flue by ANSI standard
400 ppm	▪ Level at or above which UL approved home alarms must go off within 4-15 minutes of exposure
	▪ (Air free) Level of CO allowed inside furnace flue by ANSI standard
800 ppm	▪ (Air free) Level of CO allowed inside oven flue by ANSI standard

¹ For comparison: Average indoor CO levels typically vary from 0.5 to 5 ppm (Wilson, et al., 1993). During smog episodes, atmospheric levels of CO, both indoors and outdoors can climb to 5 to 10 ppm (USEPA, 2000). ANSI = American National Standards Institute CSA = Canadian Standards Association (refers to CSA Std. 6.16-01) NIOSH = National Institute for Occupational Safety and Health OSHA = Occupational Safety and Health Administration UL = Underwriters Laboratories (refers to UL Std. #2034, Second Edition, dated October 29, 1996, with revisions through June 28, 2002).

The Occupational Safety and Health Administration (OSHA) standard for exposure to carbon monoxide prohibits worker exposure to more than 50 ppm, averaged over an 8-hour workday (29 CFR 1910.1000, Table Z-1). The National Institute for Occupational Safety and Health (NIOSH) recommends that carbon monoxide levels to which workers are exposed should not exceed a ceiling concentration of 200 ppm (NIOSH, 1972). EPA's NAAQS for outdoor air, which is intended to be protective for all segments of the population (including sensitive populations), is 9 ppm for an 8-hour average and 35 ppm for a 1-hour average (*Federal Register*, August 1, 1994). EPA has also defined Significant Harm Levels (SHL) for ambient CO levels as 50 ppm/8h average, 75 ppm/4h average, and 125 ppm/1h (40 CFR Part 51.151).

SHL are ambient pollutant concentrations that EPA defines as levels that cause significant and imminent harm to the general public. There is no EPA standard for CO in indoor air.

Listed CO alarm criteria are consistent with the use of CO alarms to warn residents of serious, life threatening levels of CO. These criteria, however, are purposefully not designed to warn of unhealthy ambient conditions addressed by EPA's Air Hazard Index or compliance with occupational standards and ceiling recommendations. Currently manufactured CO alarms that meet the UL standard must not display the CO concentration below 30 ppm, and starting in 2007 will only be required to be accurate within 30 percent of the actual CO concentration. CO alarms are not designed for low-level CO monitoring and are not appropriate for that use. For comparison, Table 6 also shows the American National Standards Institute (ANSI) standards for combustion appliances, which have remained unchanged since they were first established in 1925.

3.4.5.3 Mold Standards

Currently, there are no numerical standards or widely accepted guidelines for assessing whether there is a mold contamination problem in an area. In the U.S., there are no EPA regulations or standards for airborne mold contaminants (USEPA, 2001b). Various governmental and private organizations have, however, proposed guidance on the interpretation of fungal measures of environmental media in indoor environments (quantitative limits for fungal concentrations).

Legislators in more than a dozen states and one federal legislator have introduced bills directed at the indoor mold problem. Legislation has been enacted in Arizona and California to study and review mold contamination of indoor environments. States, such as Texas, Louisiana, and California, have enacted legislation requiring the licensing of contractors conducting mold abatement activities.

Organizations that have produced guidelines on mold prevention and/or remediation include the ACGIH, the U.S. Occupational Safety & Health Organization (OSHA), the American Industrial Hygiene Association (AIHA, 2001), the Canada Mortgage and Housing Corporation (CMHC, 1993), the Commission of the European Communities (CEC, 1993), and the World Health Organization (WHO), as well as numerous smaller and/or local organizations like the New York City Department of Health (2000). Reviews of guidance offered by various groups to assist investigators in the interpretation are available in *Bioaerosols: Assessment and Control* (ACGIH, 1999) and in Rao et al. (1996).

Recommendations reported in Rao et al. (1996) vary widely, with quantitative standards/guidelines ranging from less than 100 CFU per m³ to greater than 1000 CFU per m³ as the upper limit for airborne fungi in non-contaminated indoor environments (Rao et al., 1996). Bush and Portnoy (2001) suggest that indoor spore counts equal to or greater than 1000/m³ and colony counts on the order of 1000 to 10,000 CFU per m³ likely represent indoor fungal contamination. In a review article, Portnoy et al. (2005) concluded that, "it seems reasonable to expect that total airborne spore counts attributable to indoor sources greater than 1,000

spores/m³ indicate a concern and those greater than 10,000 spores/m³ indicate a definite problem.”

Such guidelines based on total spore counts are only rough indicators, however. Other factors in addition to indoor spore counts should also be considered. For example, the University of Minnesota Department of Environmental Health and Safety recommends consideration of several factors in addition to total spore counts when attempting to assess the severity of a mold contamination problem, including: the number of fungi indoors relative to outdoors, whether the fungi are allergenic or toxic, if the area is likely to be disturbed, whether there is or was a source of water or high relative humidity, if people are occupying the contaminated area or have contact with air from the location, and, whether there are immune compromised individuals or individuals with elevated sensitivity to molds in the area (University of Minnesota, 1996).

Given evidence that young children may be especially vulnerable to certain mycotoxins (American Academy of Pediatrics, 1998) and in view of the potential severity of diseases associated with mycotoxin exposure, some organizations support a more precautionary approach to limiting mold exposure (Burge and Otten, 1999). For example, the American Academy of Pediatrics recommends that infants under 1 year of age are not exposed at all to chronically moldy, water-damaged environments (American Academy of Pediatrics, 1998).

3.4.6 Comparability of Self-Reported Measures, Visual Surveys, and Environmental Sampling Data

Research in this area of home health assessment is ongoing. Recently, Klitzman et al. (2005a) conducted a pilot study designed to determine the prevalence of lead-based paint (LBP), vermin, mold, and safety conditions and hazards in homes and to validate observations and self-reports against environmental sampling data (70 dwellings, convenience sample, in a low-income, urban neighborhood in Brooklyn, New York). Results of the pilot show that 96% of residences contained multiple conditions and/or hazards. Frequencies of specific hazards were: LBP (80%), vermin (79%), elevated levels of airborne mold (39%), and safety hazards (100%). Comparisons of the self-reports and visual surveys to the environmental sampling data indicated that, in general, the more proximate an observed condition was to an actual hazard, the more likely it was to be associated with environmental sampling results (e.g., peeling LBP was associated with windowsill dust lead levels, and cockroach sightings by tenants were associated with *Blattella germanica* (Blat g 1) allergen levels). Conversely, the more distal an observed condition was to an actual hazard, the less likely it was to be associated with environmental sampling results (e.g., water damage, alone, was not statistically associated with elevated levels of airborne mold). In a follow-on to this study, Klitzman et al. (2005b) conducted a multihazard, multi-method intervention, addressing deteriorated lead-based paint and lead dust, vermin, mold, and safety hazards in these 70 dwellings. Dwellings received paint stabilization, dust lead cleaning, integrated pest management (IPM), mold cleaning, and safety devices, as needed. The median remediation cost for labor and materials was \$864.66 (range: \$120.00-5235.33) per dwelling. Environmental conditions were evaluated prior to, immediately following, and an average of 5 months after remediation. The authors report that the study

results indicate a comprehensive approach to hazard remediation can be highly effective and cost efficient and that overall improvements can be maintained, but note that further research is needed to clarify the most effective sampling strategies, educational and behavioral interventions, and optimal intervention frequency.

Bradman et al. (2005) conducted a study to assess the association between multiple housing disrepair indicators and cockroach and rodent infestations in the homes of 644 pregnant Latina women. Results from a visual inspection revealed that 58% of the homes had peeling paint, 43% had mold, 25% percent had water damage, and 11% had rotting wood. The researchers also rated the level of cleanliness of each home and conducted inspections for cockroach and rodent infestations. Cockroach allergen concentrations, measured in a subset of homes, were found to be significantly higher in homes with evidence of cockroach infestations than in homes without observed cockroach infestations. The presence of cockroaches was also associated with multiple housing hazards including peeling paint, water damage and lack of cleanliness. The results suggest that a visual inspection of overall housing disrepair indicators provides useful information regarding other hazards such as pest infestations.

In a randomized study on the validity of self-reported responses to questions about home safety, Hatfield et al. (2005) compared questionnaires answered by Head Start families to home inspections (n=259). The authors found that self-reported use of safety devices and practices by parents of preschool aged children was generally reliable. Answers about the presence or absence of certain safety devices (e.g., CO detectors) were generally more accurate than those about safety practices (e.g., safe medicine storage). Reliability increased when the interview was conducted in the home, although the authors hypothesized that this may have been because parents were more prepared to answer the survey questions because they had previously agreed to a home visit for solely that purpose. In addition, the parents receiving the interview at home had been told they would receive help injury proofing their homes, which may have provided additional motivation to report unsafe conditions. In a similar study, Robertson et al. (2005) evaluated the validity of parents' self-reported home safety practices concerning smoke detectors, bike helmets, car seats, and water heater temperature. The results suggest that parent self report practice of certain injury prevention behaviors (owning a car seat, hot water temperatures) is reliable, whereas self reports on other practices (working smoke detectors, properly fitting bike helmets) may be overstated.

Leaderer (2004) assessed the accuracy of questionnaire reports of cat and dog ownership and presence of cockroaches in predicting measured allergen concentrations in house dust. In the study, questionnaire results were compared to measured allergen levels collected dust samples in 932 homes of newborns living in New England. The dust analysis results were grouped into either “low” or “high” level allergen categories according to the following cut points (low first, then high): 1.0 µg/g and 8.0 µg/g for cat, 2.0 µg/g and 10.0 µg/g for dog, and 2 U/g and 8 U/g for cockroach allergen. The comparison showed that questionnaire-reported pet ownership and presence of cockroaches predicted allergen levels when in the “high” allergen level category, but was a relatively poor measure of allergen exposure at lower levels (i.e., when measured levels were near the limit of detection and the lower cut point). The authors concluded that, for epidemiologic purposes, measured concentrations of allergens are necessary.

4.0 RESEARCH NEEDS, INFORMATION GAPS, AND DISCUSSION

There are tremendous research needs and information gaps related to the assessment of residential hazards. To those involved in lead hazard control programs, this will not come as a surprise given the effort that has been required to understand and improve lead risk assessment. In many ways, creating effective assessment protocols for an overall residential hazard assessment would appear to be an order of magnitude more difficult than creating protocols only for lead exposure. Less is known about causal relationships and pathways of exposure for many of the residential hazards discussed in this paper – allergens, molds, and toxicants – than is known for lead. This understanding is crucial for selection of the most appropriate targets for assessment. In some cases, standard methods of laboratory analysis, much less standards for interpretation and comparison of those analyses, are lacking.

Beyond individual hazards are the many unanswered questions concerning multiple hazards and how multiple hazards interact physically or chemically to create an overall hazard in a home. And, of course, there is the issue of which hazards should receive the most focus in an assessment. For example, how do frequent, well-characterized, non-fatal injuries rank, compared to less frequent but potentially serious toxic exposures? Therefore, research is needed to assess the hierarchy of individual risks, as well as assess the overall risk associated with a home, including:

General Assessment Issues

- Relation of environmental concentration levels (vacuum dust, etc.) to actual exposure – risk assessment.
- Characterizing (and validating) the relationships between visual surveys (readily observable conditions), occupant reports, and environmental sampling data, and to determine how each of these can be used to assess the cumulative impact on human health.
- Better understanding of the causal relationships and pathways of exposure for health effects associated with allergens, molds, pesticides, VOCs, and other indoor toxins.
- Characterizing the extent and severity of individual residential hazards.
- Understanding interactions between risk factors for the different health endpoints associated with residential hazards.

Methodological Issues

- Characterization of sources of variability in analytical results and development of quality control samples.
- Determination of performance criteria for analytic methods (e.g., detection limits, etc.).
- Developing standards for laboratory analyses and comparison of laboratory analyses. The Environmental Law Institute (1998), in a 1998 workshop held on indoor air quality, identified the following standards as most in need of further development: biologicals, VOCs, NO₂, testing protocols for mold, aldehydes, particulates, CO, ventilation, and off-gassing of building materials and products.
- Accreditation of proficiency testing programs.

- Mold assessment issues.
 - Standard methods for mold sampling.
 - Standard methods for analysis of mold toxins.
 - Standardized methods for analysis of mold allergens.
 - Further research on fungal measurement using indicators of fungal growth (e.g., microbial VOCs).
- Allergen assessment issues.
 - Research on accuracy of home allergen tests and development of better sampling and quantitation techniques.
 - Greater standardization of assays for measuring allergen levels to allow for comparison.
- Pesticide assessment issues.
 - Standardized sample collection methods for house dust to be analyzed for pesticides from floors and surfaces.
 - Relation of environmental samples/pesticide surface loadings (vacuum dust, etc.) to actual exposure (e.g., information on exposure pathways and activity patterns of children).
- Injury assessment and control issues.
 - Identification and characterization of residential injury risk factors for different types of injuries.
 - Better understanding of parental knowledge and practices and how they relate to childhood injury.
 - Longitudinal epidemiological studies of the efficacy of low cost residential interventions in preventing childhood injuries.
- Understanding effective indicators of exposure to biological agents (e.g., whether microbial VOCs can be used as indicators of moisture problems or toxic molds).
- Developing and verifying cost-effective, quick tests for allergens and toxins.

Issues Related to Housing Structure

- Data to quantify which aspects of household water damage are related to respiratory illness.
- Areas of potential impact in building code and design to improve the indoor environment for asthmatics.
- Improved labeling of “healthy” building materials and home furnishings (e.g., reduced VOC emissions, resistance to microbial growth).

While the research and information needs are undeniably formidable, the advantage of taking a holistic approach to the assessment of residential hazards is that commonalities may emerge, such as those related to a structural characteristic of the home, a common pathway of exposure, or a common means of assessment resulting in identification of obvious, efficient targets for reducing the overall hazard in a home. These commonalities may emerge even while considerable uncertainty remains concerning many details of the individual hazards. In this way, the effect of the whole – in terms of an integrated residential hazard assessment – may actually be greater than the sum of its parts.

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